NASA CONTRACTOR REPORT

NASA CR-896

THERMAL AND MECHANICAL PROPERTIES OF A NONDEGRADED AND THERMALLY DEGRADED PHENOLIC-CARBON COMPOSITE

by W. T. Engelke, C. M. Pyron, Jr., and C. D. Pears

Prepared by
SOUTHERN RESEARCH INSTITUTE
Birmingham, Ala.
for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1967

THERMAL AND MECHANICAL PROPERTIES OF A NONDEGRADED AND THERMALLY DEGRADED PHENOLIC-CARBON COMPOSITE

By W. T. Engelke, C. M. Pyron, Jr., and C. D. Pears

Prepared under Contract No. NAS 1-5448, Task Order 3 by
SOUTHERN RESEARCH INSTITUTE
Birmingham, Ala.

for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

CONTENTS

THERMAL AND MECHANICAL PROPERTIES OF A NONDEGRADED AND THERMALLY DEGRADED PHENOLIC-CARBON COMPOSITE

By W. T. Engelke,
C. M. Pyron, Jr., and C. D. Pears
Southern Research Institute

SUMMARY

The thermophysical property study of a phenolic-carbon (fiber) material, designated as Narmco 4028, was performed under Master Agreement Contract NAS 1-5448, Task Order 3. Both the nondegraded (virgin) and thermally degraded (charred) forms were evaluated over temperature ranges of -200°F (144°K) to 750°F (673°K) for the virgin material and 1000°F (811°K) to 5000°F (3033°K) for the charred material. The thermally degraded material was prepared in an induction plasma torch with a heat flux density of 170 Btu/ft^2/sec (193 x 10^4 watts/m^2). Some chars for the thermal conductivity evaluations were made in a high temperature furnace.

The bulk and true densities of the virgin material were 85.4 lb/ft^3 (1368 kg/m^3) and 85.5 lb/ft^3 (1369 kg/m^3), respectively, indicating the porosity was nil. The bulk and true densities (obtained by pulverizing bulk pieces) of the plasma char were 73.9 lb/ft^3 (1184 kg/m^3) and 93.0 lb/ft^3 (1490 kg/m^3), respectively, indicating a porosity of 20%. The furnace char had a somewhat higher porosity.

The thermal conductivities in the with and across fiber directions were obtained on both the virgin and charred material. An ASTM C177 guarded hot plate was employed for the virgin material, and a radial inflow apparatus for the charred material. The thermal conductivity of the virgin material in the across fiber direction increased from 6.2 x 10^{-5} Btu/sec/ft/°F (0.39 W/m/°K) at -200°F (144°K) to a maximum of 12.5 x 10^{-5} Btu/sec/ft/°F (0 78 W/m/°K) at 420°F (480°K). In the with fiber direction, the conductivity was considerably higher, as expected, and increased from 7.3 x 10^{-5} Btu/sec/ft/°F (0.45 W/m/°K) at -200°F (144°K) to a maximum of 20.5 x 10^{-5} Btu/sec/ft/°F (1.28 W/m/°K) at 590°F (583°K).

For the charred materials, the thermal conductivity in the across fiber direction of specimens prepared in the plasma torch increased from 30 x 10^{-5} Btu/sec/ft/°F (1.87 W/m/°K) at 1000°F (811°K) to 157 x 10^{-5} Btu/sec/ft/°F (9.78 W/m/°K) at 5000°F (3033°K). The values obtained in the same direction

on a char prepared in the furnace were higher at the lower temperatures, increasing from 62 x 10^{-5} Btu/sec/ft/°F (3.86 W/m/°K) at 1000°F (811°K) to 150 x 10^{-5} Btu/sec/ft/°F (9.34 W/m/°K) at 5000°F (3033°K). The higher conductivity at the lower temperatures exhibited by the furnace char suggested a higher degree of graphitization of the matrix or reinforcement due to the longer exposure times. The photomicrographs of the charred material indicated a difference. Even though there was a difference between the two chars, it does appear that furnace chars can be used to predict flight performance by analytical adjustment. The thermal conductivity of the plasma char in the with fiber direction increased from 80 x 10^{-5} Btu/sec/ft/°F (4.98 W/m/°K) at 1000°F (811°K) to 365 x 10^{-5} Btu/sec/ft/°F (22.74 W/m/°K) at 4800°F (2922°K).

The enthalpy and heat capacity of both the virgin and charred materials were determined by utilizing the drop-type adiabatic cup calorimeter for the virgin material and the ice calorimeter for the charred material. The heat capacity increased from 0.14 Btu/lb/°F (586 J/kg/°K) at 150°F (339°K) to 0.39 Btu/lb/°F (1632 J/kg/°K) at 750°F (673°K). For the charred material the heat capacity increased from 0.39 Btu/lb/°F (1632 J/kg/°K) at 1000°F (811°K) to 0.52 Btu/lb/°F (2176 J/kg/°K) at 4500°F (2756°K).

The total normal emittance of the charred material was obtained by comparing the irradiance from the specimen to that from a cavity-type blackbody maintained at the same temperature. The emittance remained constant at 0.75 from 1600°F (1144°K) to 3700°F (2311°K) and above this temperature decreased slightly to 0.70 at 4200°F (2589°K).

A general comparison of the thermal properties of the Narmco 4028 material with those of the phenolic-nylon previously evaluated under NAS 1-2978 was performed. Undoubtedly the carbon fibers caused the conductivity to be considerably higher in both the virgin and charred materials and the heat capacity to be lower in the virgin material. The emittance was lower for the Narmco 4028 char, consistent with the smoother and more reflective characteristic of the surface.

INTRODUCTION

This is the final report on the thermophysical property evaluation of a phenolic-carbon fiber material under NASA Master Agreement Contract No. NAS 1-5448, Task Order 3. The phenolic-carbon fiber material, a commercial ablative composite having the designation of Narmco 4028, was evaluated in both the nondegraded (virgin) and thermally degraded (charred) forms. The

thermal conductivity, heat capacity and room temperature density were determined on both the virgin and charred material, and the total normal emittance was determined on the charred material only. The temperature ranges were -200°F (144°K) to 750°F (673°K) for the evaluation of the virgin material and 1000°F (811°K) to 5000°F (3033°K) for the charred material.

SPECIMEN MATERIAL

The Narmco 4028 material was supplied by the NASA Langley Research Center in a block 11 inches (27.9×10^{-2} meters) in diameter by $4\frac{1}{2}$ inches (11.4×10^{-2} meters) thick. The material was a phenolic resin reinforced with $\frac{1}{4}$ inch (0.6×10^{-2} meters) carbon fibers. The molding compound was manufactured by Narmco Materials Division, Whittaker Corporation. A complete description of the compound is included in Table 1. The molding and curing of the material was performed by the NASA Langley Research Center under the following schedule:

1. Hot-pressing in a mold at 3200 psi (22.1×10^6 N/m^2) while in a vacuum and at a temperature of 320°F (433°K) for three hours. Uniform temperatures were maintained during the heating cycle to 320°F (433°K).

2. Post cured according to the following temperature cycle:

   (a) start at 125°F (325°K), hold 1 hour
   (b) raise temperature 25°F/hr (14°K/hr) to 200°F (366°K), hold 4 hours
   (c) raise temperature 10°F/hr (5.6°K/hr) to 250°F (394°K), hold 8 hours
   (d) raise temperature 5°F/hr (2.8°K/hr) to 350°F (450°K), hold 4 hours
   (e) cool to room temperature at 40°F/hr (22°K/hr)

To further define the virgin material, the bulk and true densities were determined; the values were as follows:

Bulk density - 85.4 lb/ft^3 (1368 kg/m^3)
True density - 85.5 lb/ft^3 (1369 kg/m^3)

The above values indicate that the porosity of the material was essentially zero. However the density was slightly lower than the density of 87.4 lb/ft^3 (1400 kg/m^3) specified by Narmco Materials Division (see Table 1).

PREPARATION AND DESCRIPTION OF THE CHARRED MATERIAL

The charred Narmco 4028 material was prepared mainly by utilizing an induction plasma torch. Some chars were also prepared in the high temperature furnaces for comparison with the degraded structure of the chars formed in the plasma.

Char Preparation in the Induction Plasma Torch

The induction plasma torch is basically a quartz tube which is surrounded at one end with a five turn rf coil, and has the other end inserted in a brass housing which supplies a turbulent swirl flow of argon. The rf coil is energized by a Lepel 25 kw power supply at a frequency of approximately 4.3 mc. The plasma is initiated by inserting a graphite rod in the field of the coil while maintaining an argon flow rate of 25 to 30 scfh (19.7×10^{-5} to 23.6 m^3/sec). The graphite rod heats and causes the argon to ionize, thus initiating the plasma. The plasma is then sustained by the rf field. The argon flow is increased, mixed with nitrogen, and the power level is increased to provide the desired plasma characteristics.

To prepare the chars under this program, the torch was operated with 30% nitrogen and 70% argon at close to maximum power. At higher nitrogen flow rates the plasma jet became unstable. If power was increased to stabilize the jet, arcing would occur between the turns of the coil.

Heat flux densities, measured at the above conditions using a copper slug calorimeter, averaged about 170 Btu/ft^2/sec (193×10^4 watts/m^2) at a distance of 1 inch (2.54×10^{-2} meters) from the end of the quartz tube. This level was sufficient to produce the required chars of proper quality.

The copper slug calorimeter used to determine the heat flux densities was basically a copper disc of known weight and size instrumented with a thermocouple and mounted in a refractory brick. Heat flux densities were computed from measurements of the temperature rise of the copper disc versus time (monitored by an X-Y recorder). It was found during the initial runs that the induced voltage caused enough current flow through the

thermocouple circuit to burn out the wire. This current drain would also extinguish the plasma. Therefore, the rate of temperature rise was monitored by obtaining the slug temperature immediately before and after exposure to the flame and measuring the length of time during exposure. The thermocouple circuit was switched open during flame exposure. This method, although approximate, did confirm that sufficient heat flux density was available to make the chars.

The specimens employed for exposure to the plasma jet were either $1\frac{1}{4}$ inches (3.2×10^{-2} meters) square or $2\frac{1}{4}$ inches (5.7×10^{-2} meters) square and were mounted in a refractory brick holder. The specimen surface was located 1 inch from the end of the quartz tube and retained in the jet for 180 seconds. Immediately after the run the specimen was inserted into a container that was continuously being flushed with nitrogen. All power settings and gas flow rates were maintained constant for all runs and were equal to those employed during the heat flux density determinations. Surface temperatures of the specimens were monitored with an optical pyrometer to determine the consistency of the charring conditions under each run. The pyrometer data obtained were not corrected for effects of specimen emittance and flame characteristics; however, these data ascertained the consistency of all the runs. The pyrometer readings also provided an approximate temperature profile on the surface of the specimens. This profile is shown in Figure 1.

Under the above conditions the specimen was fully degraded to a depth of approximately $\frac{3}{8}$ of an inch (0.9×10^{-2} meters). All specimens were machined from the central area of the charred surface.

Char Preparation in the High Temperature Furnaces

A separate set of charred material was prepared in the high temperature furnaces, which are described in Reference 1. Sufficient material was degraded to permit a study of the physical structure and to determine the thermal conductivity in the across fiber direction. This was done to perform an analysis of the variations between the two types of charred material.

The high temperature furnaces employed a graphite heating element which was heated resistively by a low voltage, high amperage power supply. Temperatures up to 5800°F (3478°K) can be obtained. A helium atmosphere was maintained within the furnace throughout the run.

The virgin material was cut in pieces slightly larger than the specimens and held within a graphite cage inserted in the furnace. Ends of the heater tube were properly insulated to maintain isothermal conditions within the hot zone. The specimens were degraded under the following schedule:

1. Heated to 750°F (672°K) in 2 hours
2. Maintained at 750°F (672°K) for 1 hour
3. Heated to 4000°F (2477°K) in 3 hours
4. Maintained at 4000°F (2477°K) for 2 hours
5. Cooled to room temperature in 1 to 2 hours

Char Description

The chars prepared were fully degraded and the structure was porous and exhibited many fine cracks. Even with the pores and cracks, the structure was rather firm and allowed the machining of all specimens without the aid of a reinforcing filler like that required for the phenolic-nylon chars evaluated under the previous NASA Contract NAS 1-2978. To further define the charred material, density determinations and photomicrographs were made.

The bulk and true densities were determined on duplicate specimens of the plasma char. The average bulk density was 73.9 lb/ft^3 (1184 kg/m^3), and the true density was 93.0 lb/ft^3 (1490 kg/m^3), corresponding to a porosity of 20%. The bulk density of the furnace char was about 10% lower than that of the plasma char, the average value being 64.3 lb/ft^3 (1030 kg/m^3). This indicates a higher porosity for the furnace chars which was obvious upon visual inspection. The furnace chars exhibited more cracks, were coarser and more porous than the plasma char. This is illustrated by comparing the photographs of the conductivity specimens shown in Figure 8.

The porosity values just discussed were generated for the chars by comparing the densities of bulk pieces and a pulverized sample of the bulk pieces. No attempt has been made at this stage to generate the true density of the pulverized samples. This may be necessary for a detailed thermal analysis as is being conducted in current programs.

The photomicrographs shown in Figure 2 of both the plasma char and furnace char provided both confirmation of visual observations plus additional information. The figure illustrates a significant difference between the

structures of the two chars. The plasma char appeared to have a high porosity with little or no matrix between the carbon fibers. The furnace char appeared to have more matrix with better bonding between the fibers although its density was actually lower. The photomicrograph of the plasma char is somewhat misleading. The specimen was difficult to polish and it is probable that the matrix between the fibers (due to its weak degraded structure) was pulled out during polishing, or it did not polish, thus leaving the dark areas between the fibers. The low 20% porosity of the plasma char was consistent with the presence of the degraded matrix. We believe the better continuity of the furnace char, apparent from the photomicrograph, was caused by the less violent birth of the char and the more ordered structure of the degraded resin which provided a better structure for polishing. A more graphitized structure of the matrix within the furnace char would be caused by the longer period (2 hours) of charring at 4000°F (2477°K) when compared with the exposure time of the plasma char (180 seconds). The thermal conductivity curves, obtained on both materials and discussed in the following section, also support this conclusion.

THERMAL CONDUCTIVITY

The thermal conductivity was determined in two directions (with and across fiber) on both the virgin and charred material. For the virgin material, data were obtained from -200°F (144°K) to 750°F (673°K). The temperature range for the charred material was from 1000°F (811°F) to 5000°F (3033°K) with the data being obtained during heating and cooling cycles. The plasma char was evaluated in both the with and across fiber directions and the furnace char was only evaluated in the across fiber direction.

The thermal conductivity of the virgin material was determined using an ASTM C177 guarded hot plate apparatus. The char specimens were evaluated in the radial inflow apparatus.

Apparatus and Procedures

ASTM guarded hot plate. - The 3-inch (7.6×10^{-2} meters) diameter ASTM C177 guarded hot plate apparatus employed for the thermal conductivity evaluation of the virgin material is described in Reference 1 and briefly below.

Basically this apparatus consisted of a central heater plate surrounded by a guard heater, each separately controlled. The guard ring was maintained at the same temperature as the central to maintain the heat flow normal to the specimen surfaces. The heater plate was sandwiched between layers of filler pads, hot face thermocouples, the specimen, cold face thermocouples, filler pads, a copper plate, and finally a cold plate to dissipate the heat. In addition to the thermocouples in contact with the specimen, thermocouples were located in the central heater and the copper cold plates. The specimens were carefully prepared to obtain flat, smooth surfaces and minimize interface resistances. Intimate contact was provided at all interfaces by pressing the entire assembly together with a screw loaded frame.

Filler pads of gum rubber were used from -200°F (144°K) to 150°F (399°K). Above 150°F (339°K), Fiberfrax paper was used for the filler pads with a sheet of gum rubber at the cold plate. Overlapping data were obtained at the 150°F (339°K) temperature level using both filler arrangements to provide a check on contact resistance resulting from irregularities of the specimen surface.

To obtain mean temperatures of -200°F (144°K) liquid nitrogen was circulated through the cold plates. For higher temperatures, chilled trichloroethylene and water cooling were employed. When data points were obtained below room temperature, the apparatus was enclosed in a plastic bag which was purged with dry helium to eliminate frosting and moisture condensation.

During the runs, the change in thickness at the higher temperature levels was monitored. This was accomplished by cutting slots in the edges of the specimens, placing pads of 0.005 inch (0.013×10^{-2} meters) stainless steel shim stock above and below these slots and measuring the distance between the shims with a hole gage. Measurements were taken at each temperature level. In general, the thickness changed by about 3% or less during the run, and this change usually occurred at the maximum temperature.

This ASTM C177 apparatus has been used extensively in prior programs to determine the thermal conductivities of plastics and other materials. In such programs the maximum uncertainty has consistently averaged less than five percent, based on calibrations with Pyrex and Plexiglas standards.

Radial inflow apparatus. - The thermal conductivity of the char specimens was determined in the radial inflow apparatus by employing a modified procedure. The basic apparatus is described in Reference 1.

Briefly, the test section was heated radiantly in a high temperature furnace which employed a cylindrical graphite resistance heating element. The heat flowed radially inward through the specimens to a central water flow calorimeter. Water temperatures in the calorimeter were indicated by thermocouples in the water stream located one-half inch (1.27×10^{-2} meters) apart axially, and heat flow through the specimen gage section was computed from measurements of water flow rate and temperature rise. Specimen temperatures were measured in two axially drilled holes located on two different radii. Below 2000°F (1366°K) temperature measurements were taken with chromel/alumel thermocouples; above this temperature, measurements were taken by sighting the bottom of the holes through an optical pyrometer and a right angle mirror device. Axial conduction in the specimen was minimized by (1) insulating the specimen on each end with graphite sleeves filled with thermatomic carbon, (2) by making the specimen length at least twice the gage length, and (3) by providing an isothermal hot zone over at least twice the specimen length.

Thermal conductivity was calculated from the standard relation

$$k = \frac{ql}{A\Delta T} \tag{1}$$

where k is the thermal conductivity, A is the log mean cylindrical area, and l is the radial distance over which ΔT is measured.

The specimen configuration used to determine the conductivity in the with fiber direction consisted of a stack of eight one inch diameter by $\frac{1}{4}$ inch (0.635×10^{-2} meters) thick discs machined to the proper configuration to form the normal cylindrical specimen as shown in Figure 3.

To measure the thermal conductivity of the chars in the across fiber direction, the technique described above was modified as follows: Four char strips, approximately $\frac{3}{8}$ inch (0.95×10^{-2} meters) wide by $\frac{1}{4}$ inch (0.635×10^{-2} meters) thick by 2 inches (5.08×10^{-2} meters) long were arranged symmetrically as shown in Figure 4. For this configuration, it was necessary that isothermals in the specimen be perpendicular to the thickness direction. This condition was achieved by placing thin strips of pyrolytic graphite at the inner surfaces of the char strips. Because of the high anisotropy of this material (the conductivity is approximately 50 times greater in the "a" direction than in the "c", or thickness, direction) the

isotherms were forced to assume a square configuration. Heat flow other than through the specimens was eliminated essentially by using thermatomic carbon of extremely low thermal conductivity (approximately 0.1 Btu/hr/ft^2/°F/in. or 0.014 W/m/°K) as packing at the edges of the specimens. The space around the calorimeter was packed with graphite powder. Temperatures were measured at two locations in the strips, using the methods described above. This procedure was employed with good results under previous Task Orders 2 and 3 of Contract NAS 1-2978, and is reported in NASA TN D-2991 (Reference 1).

During each run, the thermal conductivity was determined while heating from 1000°F (811°K) to 5000°F (3033°K) at 500°F (278°K) intervals and cooling from 5000°F (3033°K) to 1000°F (811° K) at 1000°F (555°K) intervals. The cooling data were obtained in order to assess whether any changes occurred in the conductivity resulting from the high temperature exposures.

Data and Results

Virgin material. - The thermal conductivity data obtained in the across and with fiber directions are shown in Figures 5 and 6 and Tables 2 and 3. The thermal conductivity in the across fiber direction increased from 6.2 x 10^{-5} Btu/sec/ft/°F (0.39 W/m/°K) at -200°F (144°K) to a maximum of 12.5 x 10^{-5} Btu/sec/ft/°F (0.78 W/m/°K) at 420°F (489°K). In the with fiber direction the conductivity was considerably higher, as expected, and increased from 7.3 x 10^{-5} Btu/sec/ft/°F (0.45 W/m/°K) at -200°F (144°K) to a maximum of 20.5 x 10^{-5} Btu/sec/ft/°F (1.28 W/m/°K) at 590°F (583°K).

In applying the values for the with fiber conductivity, the length of heat flow path must be considered. The fibers being $\frac{1}{4}$ inch (0.64 x 10^{-2} meter) in length would provide a direct heat path through any specimen less than $\frac{1}{4}$ inch (0.64 x 10^{-2} meter) thick and thereby increase the observed conductivity over values obtained on thicker specimens. Since the specimens employed for the above data in the with fiber direction were about $\frac{3}{8}$ inch (0.95 x 10^{-2} meter) thick (thickness being in the directions of the fiber for these specimens) these data can only be applied for applications where the length of the heat flow path is greater than $\frac{1}{4}$ inch (0.64 x 10^{-2} meter).

The above values are slightly lower than some previous data obtained here on phenolic-carbons, probably due to the higher percentage (50%) of the phenolic in the material evaluated in this program. In comparing the data with those reported by Melpar[1] for the same phenolic-carbon material, one observes that our data for both the with fiber and across fiber directions were considerably higher than Melpar's for which no directional orientation was specified. It seems doubtful that our values are high since we have considerable experience with ASTM C177, see Reference 3, and since most systematic errors that can escape even the most extensive care in the operation of this equipment tend to give values that are a few percentage points low rather than high. The material evaluated here was molded at higher pressures, 3200 psi (22.1 x 10^6 N/m^2) compared to 2000 psi (13.8 x 10^6 N/m^2), for a longer period of time (3 hours compared to $1\frac{1}{2}$ hours).

Charred material. - The thermal conductivity values of both plasma and furnace prepared chars in the across fiber direction are shown in Figure 7 and Tables 4 and 5. As can be seen from the figure, the plasma char exhibited values that increased from 30 x 10^{-5} Btu/sec/ft/°F (1.87 W/m/°K) at 1000°F (811°K) to 157 x 10^{-5} Btu/sec/ft/°F (9.78 W/m/°K) at 5000°F (3033°K). The values obtained on the furnace char increased from 62 x 10^{-5} Btu/sec/ft/°F (3.86 W/m/°K) at 1000°F (811°K) to 150 x 10^{-5} Btu/sec/ft/°F (9.34 W/m/°K) at 5000°F (3033°K). Thus the conductivity of the furnace char was higher than that of the plasma char at the lower temperatures, but rather good agreement was obtained at temperatures above 3500°F (2200°K), where the temperatures were closer to those experienced in flight conditions. The thermal conductivity values for the plasma char obtained during cooling were higher than those obtained during heating; however, the values for the furnace char obtained during cooling agreed well with the values obtained during heating.

The fact that the furnace char exhibited a higher conductivity at the lower temperatures substantiated the previous conclusion drawn from the photomicrographic evaluations that the resin within the furnace char developed a higher degree of graphitization. The more graphitized structure would provide higher values at the lower temperatures where the main mode of heat transfer is solid conduction. At the higher temperatures where radiation becomes predominant and the matrix contribution is relatively small, the conductivities of the two chars merged since the

porosities were similar. The repeatable cooling data obtained on the furnace char also suggested a more stable composite exhibiting a higher degree of graphitization for the resin.

The cooling data must be accepted with some reservations, since they are subject to errors resulting from thermal motions which occur during cooling. Such motions can allow shifting and loosening of the specimens, insulation and packing, resulting in nonuniform heat flow patterns, heat shorts and other undesirable effects. While some loosening of the assemblies and cracking within the thermatomic carbon insulation were noted during post run inspections, these changes were not severe. (See Figure 8 for photographs of two across-fiber specimens before and after the runs.) From observations of the specimens and the data, we concluded that the increase in measured conductivity during cooling resulted primarily from additional graphitization of the char during the heating cycle. Similar results have been observed in prior evaluations on chars which were evaluated to temperatures of 4000°F or higher, then rerun using a new buildup. The conductivity increased on each successive run over most of the temperature range. The reader is referred to a paper by the authors (Reference 4) for a more detailed discussion of this phenomenon.

Photomicrographs of a plasma char specimen and a furnace char specimen taken before and after the conductivity determinations are shown in Figures 9 and 10, respectively.

The thermal conductivity data for the plasma char in the with fiber direction are shown in Figure 11 and Table 6. The values increased from 80×10^{-5} Btu/sec/ft/°F (4.98 W/m/°K) at 1000°F (811°K) to 365×10^{-5} Btu/sec/ft/°F (22.74 W/m/°K) at 4800°F (2922°K). These data were approximately 2 to 3 times higher than the conductivity of the plasma char in the across fiber direction. The data obtained during the cooling cycle remained rather high and were greatly scattered on the return to 1000°F (811°K). This was probably due mainly to the separation and warpage of the discs and probably partly to the structural change mentioned above. The photograph in Figure 12 illustrates the specimen assembly after cool down.

HEAT CAPACITY

The enthalpy and heat capacity were determined on both the virgin and charred material. The data were determined from -200°F (144°K) to 750°F (673°K) for the virgin material and from 1000°F (811°K) to 5000°F (3033°K) for the charred material.

Apparatus and Procedures

Adiabatic calorimeter. - This apparatus is fully described in Reference 1 and only the major features are described here. Briefly, the enthalpy of a specimen at a particular temperature was determined by dropping the heated or cooled specimen into a cup which was maintained adiabatic. Enthalpy was determined from the weight of the specimen and the temperature change of the cup. The calorimeter cup was placed in an insulated container which was immersed in a bath of ethylene glycol. Adiabatic conditions were maintained by heating or cooling the bath. The specific heat was calculated from the slope of the enthalpy versus temperature curve. This slope was determined by averaging both a graphical solution and an analytical solution in which the enthalpy curve was fitted by a least squares approach and the resulting equation differentiated to obtain the specific heat.

The temperature range of the adiabatic calorimeter equipment was extended from -50°F (228°K) to -250°F (117°K) by cooling the specimen in a chamber specially designed for inserting within the cold box described in Reference 1. The cooling chamber was constructed of two concentric cylinders, the specimen being contained within the central cylinder. The annulus between the cylinders was filled with liquid nitrogen. With this system, temperatures of -250°F (117°K) were readily obtained. A continuous dry helium purge was maintained to eliminate any "frosting" on the specimen.

Ice calorimeter. - The drop type ice calorimeter employed to determine the enthalpy of the degraded material is fully described in Reference 1.

This calorimeter employed a cup surrounded by an ice mantle. The enthalpy determinations were made by dropping the heated specimen into the apparatus and measuring the volume of ice melted as the specimen cooled 32°F (273°K). Specific heat was calculated from the slope of the enthalpy versus temperature curve.

Data and Results

Virgin material. - The enthalpy and heat capacity values obtained on the virgin material are shown in Figure 13 and Table 7. The heat capacity increased from 0.14 Btu/lb/°F (586 J/kg/°K) at -150°F (172°K)

to 0.39 Btu/lb/°F (1632 J/kg/°K) at 750°F (672°K). These values are in general agreement with the heat capacity of the phenolic-carbon materials evaluated here in prior programs. It was also observed that these values were considerably lower than those obtained on the phenolic-nylon material evaluated under NAS 1-2978. This was expected since the heat capacity of carbon is considerably lower than that of nylon.

Charred material. - The enthalpy and heat capacity data of the plasma char are shown in Figure 14 and Table 8. The heat capacity increased from 0.39 Btu/lb/°F (1632 J/kg/°K) at 1000°F (811°K) to 0.52 Btu/lb/°F (2176 J/kg/°K) at 4500°F (2756°K). These values compared well with the heat capacity of the charred low-density phenolic-nylon materials evaluated under NAS 1-2978, indicating a similar carbonaceous character of the materials.

TOTAL NORMAL EMITTANCE

The total normal emittance of the charred material degraded with the plasma torch was determined. This was performed by comparing the irradiance from the specimen to that from a cavity-type blackbody maintained at the same temperature. The temperature range covered was from 1500°F (1089°K) to 4200°F (2589°K).

Apparatus and Procedure

A complete description of the apparatus and procedure employed for the emittance determinations is included in Reference 1. Briefly, the specimen was heated in an induction furnace and its irradiance was monitored by a 160-junction thermopile calibrated against a cavity type blackbody to about 5200°F (3144°K). An optical pyrometer was employed to monitor temperature of the specimen. The assumption of graybody emittance and the use of the Wien and Stefan-Boltzmann equations permitted an iterative calculation of true temperature and emittance.

Temperatures were not obtained below 1500°F (1089°K) since the irregular surface of the char inhibited the proper contact required for a surface thermocouple. Temperatures above 4300°F (2644°K) were not obtained due to the destruction of the tungsten heating discs under the specimen. The high heat flux created a high temperature gradient across the specimen which accounted for the melting of the tungsten disc when the temperature of the exposed surface of the specimen exceeded 4200°F (2589°K).

The specimens were prepared by cutting discs $\frac{1}{2}$ inch (1.27×10^{-2} meter) diameter by $\frac{1}{8}$ to $\frac{1}{16}$ inch (0.32×10^{-2} to 0.16×10^{-2} meter) thick from the charred material. The top surface of the char was unaltered after exposure to the plasma jet.

Data and Results

The values of total normal emittance are shown in Figure 15 and Table 9. The emittance remained constant at 0.75 from 1600°F (1144°K) to 3700°F (2311°K) and above this temperature decreased slightly to 0.70 at 4200°F (2589°K). These values were lower than those of the phenolic-nylon char evaluated under NAS 1-2978. This was expected, however, from the different colors and surface characteristics of the two charred materials. The phenolic-nylon char exhibited a very coarse, porous, and cracked surface that was a dull black in color. The phenolic-carbon however, had a solid surface which contained a network of exposed carbon fibers that resulted from the degradation and ablation of the phenolic resin. The carbon fiber had a smooth finish which created a satin black surface texture and color. This satin black characteristic was consistent with the lower emittance values.

DISCUSSION

In this section, the thermal characteristics of the Narmco 4028 material are summarized and compared with other ablative composites. Several composite curves were prepared and are presented in Figures 16 and 17.

The thermal properties of the virgin material are shown in Figure 16. As can be seen from the figure, the thermal conductivity of the virgin Narmco 4028 was considerably higher than that of the low-density phenolic-nylon evaluated under the previous NASA Contract NAS 1-2978, but fair agreement, particularly in the across fiber direction, was obtained with a 30% phenolic-carbon fabric evaluated previously under Air Force Contract AF 33(657)-8594 and reported in Reference 2. Due to the carbon fiber reinforcement, the thermal conductivity in the across fiber direction was 5 to 8 times higher than that of the phenolic-nylon. Since in the Narmco 4028 material the fibers were aligned in parallel layers some anisotropy existed, but it was not as great as that exhibited for the phenolic-carbon fabric material evaluated previously. Since the chopped fibers in the Narmco

material did not present a continuous thermal path, the conductivity in the with fiber direction was lower than that of the prior fabric reinforced material; however, the conductivities of the two materials were about the same in the across fiber direction. As mentioned earlier, the with fiber conductivity would be higher in specimens of less than $\frac{1}{4}$ inch in thickness due to the continuity of the fibers from one surface to the other.

As shown in Figure 16, the enthalpy and heat capacity of the virgin Narmco 4028 material were considerably lower than those of the low-density phenolic-nylon. The lower values for the Narmco 4028 were expected since carbon has a lower heat capacity than nylon. Fair agreement was obtained with a prior phenolic-carbon material.

The charred Narmco 4028 exhibited very good structure after the high temperature exposures. Its dimensional stability and strength far exceeded that of the phenolic-nylon chars evaluated under the previous NASA contract. This was demonstrated by its machinability. Recall that it was impossible to machine the phenolic-nylon without first impregnating it with a filler (polyalphamethylstyrene).

Figure 17 includes the composite curves on the thermal properties of the charred material. The thermal conductivity of the Narmco 4028 char in the across fiber direction was approximately twice that of the three phenolic-nylon chars; however, the data agreed well with data in the across fiber direction on a carbon filled phenolic-carbon composite (MX4926) evaluated here previously. The MX4926 material was charred at 4000°F (2477°K) in a furnace for 2 hours. In the with fiber direction, the MX4926 char exhibited values considerably higher than those of the Narmco 4028 char. The continuity of the fabric in the MX4926 undoubtedly caused the greater degree of anisotropy.

A general conclusion which is drawn from the above comparison is that the composition and structure of the virgin material do have a direct influence on the conductivity of the char. The phenolic-nylon chars exhibited lower conductivities than the phenolic-carbon char which contained the carbon fabric reinforcement. Also greater anisotropy was exhibited with the fabric reinforced composite due to the better continuity of the fabric when compared with the fibers.

Recall the higher conductivity exhibited by the Narmco 4028 char prepared in the high temperature furnace when compared to the values obtained on the char exposed to the plasma torch. As discussed in detail

before, the extended exposure times of the chars prepared in the furnace probably created a more fully graphitized structure of the resin, therefore causing the higher thermal conductivity. The char prepared in the plasma torch at shorter exposure times may be more representative of reentry conditions. The agreement in values obtained from the two chars was good enough to suggest that furnace chars can be used to develop analytical methods for predicting flight performance.

The enthalpy and heat capacity of the charred Narmco 4028 material were in good agreement with the values for the charred low-density phenolic-nylon materials as shown in Figure 17. This indicates similar chemical structure of the carbonaceous composites formed.

As mentioned in the previous section and as demonstrated in Figure 17, the emittance exhibited by the Narmco 4028 char was lower than that of the phenolic-nylon char due to the smoother and more reflective surface of the Narmco 4028 char.

In general, when comparing the Narmco 4028 material with the low-density phenolic-nylons in ablative applications, the Narmco 4028 material has the advantage of better mechanical stability but the disadvantage of higher thermal conductivity.

Southern Research Institute
Birmingham, Alabama
February 10, 1967

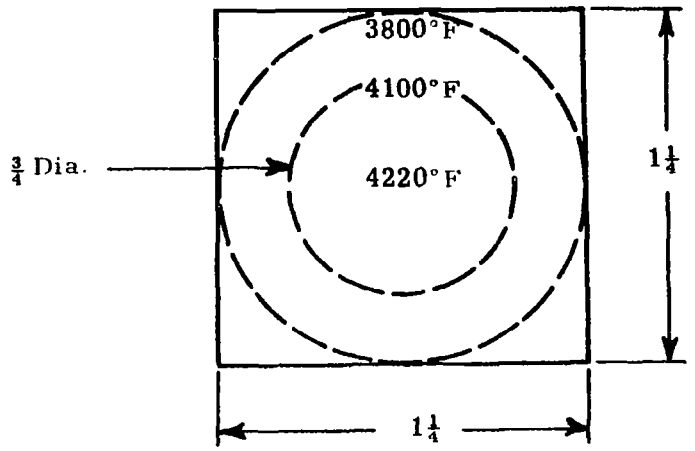
REFERENCES

1. Wilson, Gale R. (compiler): Thermophysical Properties of Six Charring Ablators from 140° to 700°K and Two Chars from 800° to 3000°K. NASA TN D-2991, October 1965.

2. Pears, C. D.; W. T. Engelke; and J. D. Thornburgh: The Thermophysical Properties of Plastic Materials from -50°F to over 700°F. ML TDR 64-87, Parts I and II, Southern Research Institute, March 1964 and April 1965.

3. Pears, C. D.; W. T. Engelke; and J. D. Thornburgh: The Thermal and Mechanical Properties of Five Ablative Reinforced Plastics from Room Temperature to 750°F. AFML-TR-65-133, Southern Research Institute, April 1965.

4. Pears, C. D.; and C. M. Pyron, Jr.: The Thermal Conductivity of Ablative Materials by the "Boxing" Analysis. Paper presented at the Fifth Thermal Conductivity Conference (Denver, Colorado) October 1965.

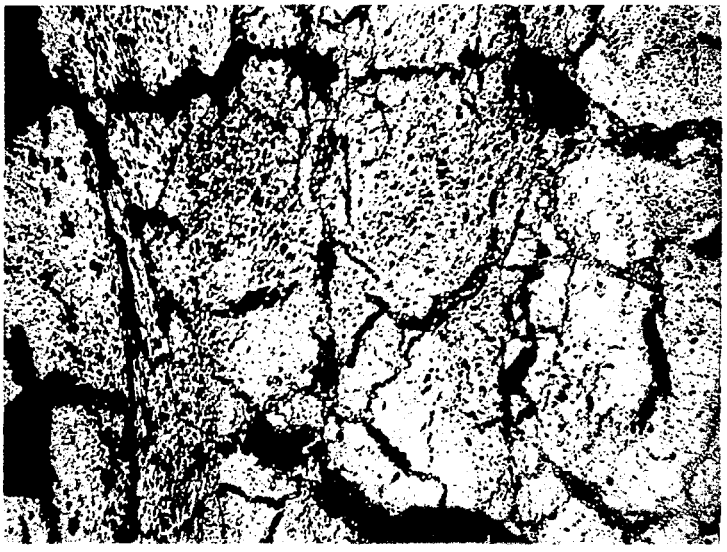


Note: Temperatures obtained with optical pyrometer and are uncorrected for effects of surface emittance and transmittance of plasma.

Figure 1. Typical surface temperature profiles observed on Narmco 4028 specimens during plasma jet exposures

Thickness

Char produced with plasma (50X)



Thickness

Char produced in high temperature furnace (50X)

Figure 2. Typical photomicrographs of Narmco 4028 char

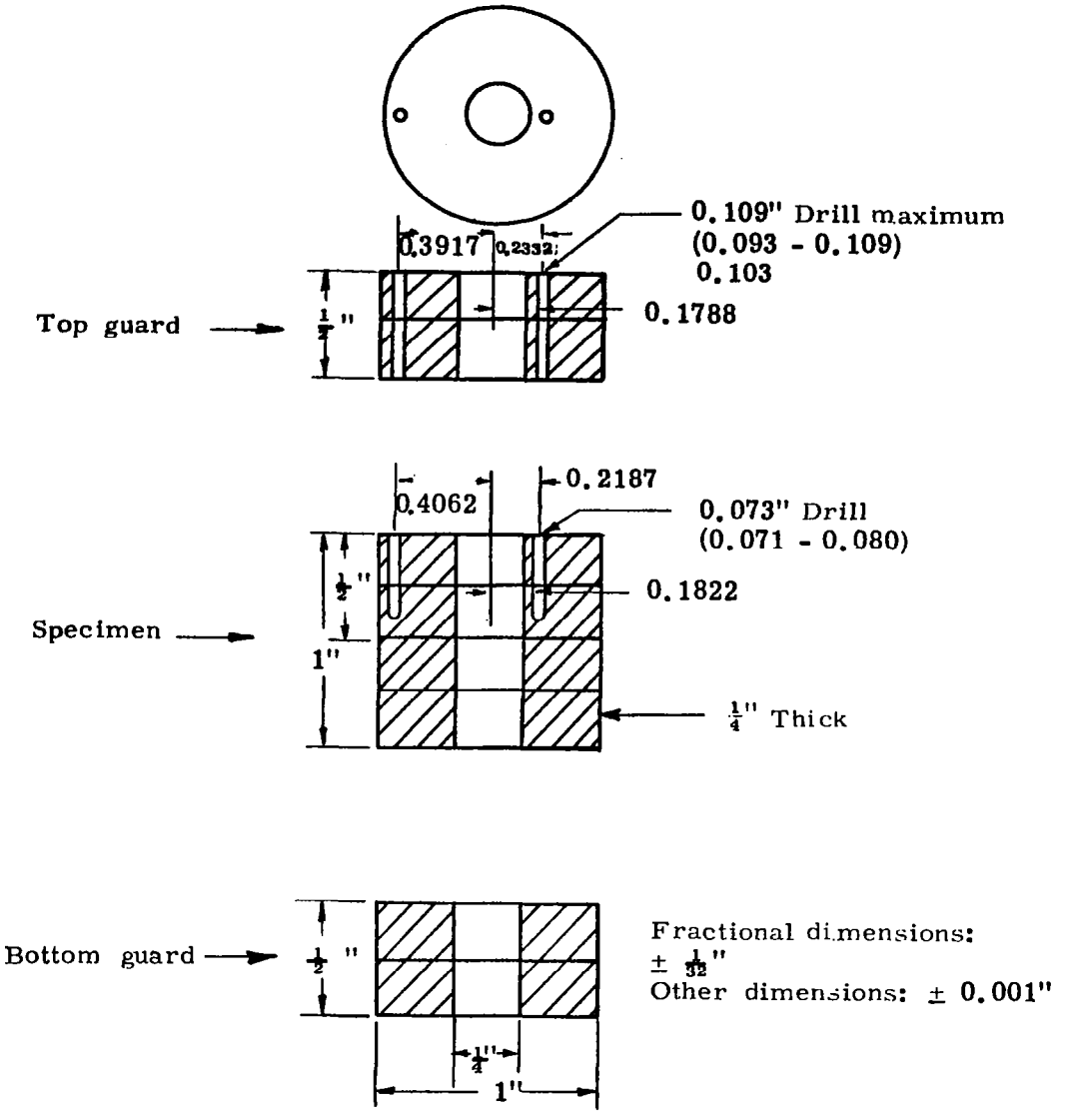


Figure 3. Specimen configuration used in radial inflow apparatus to determine the thermal conductivity of Narmco 4028 char in the with fiber direction

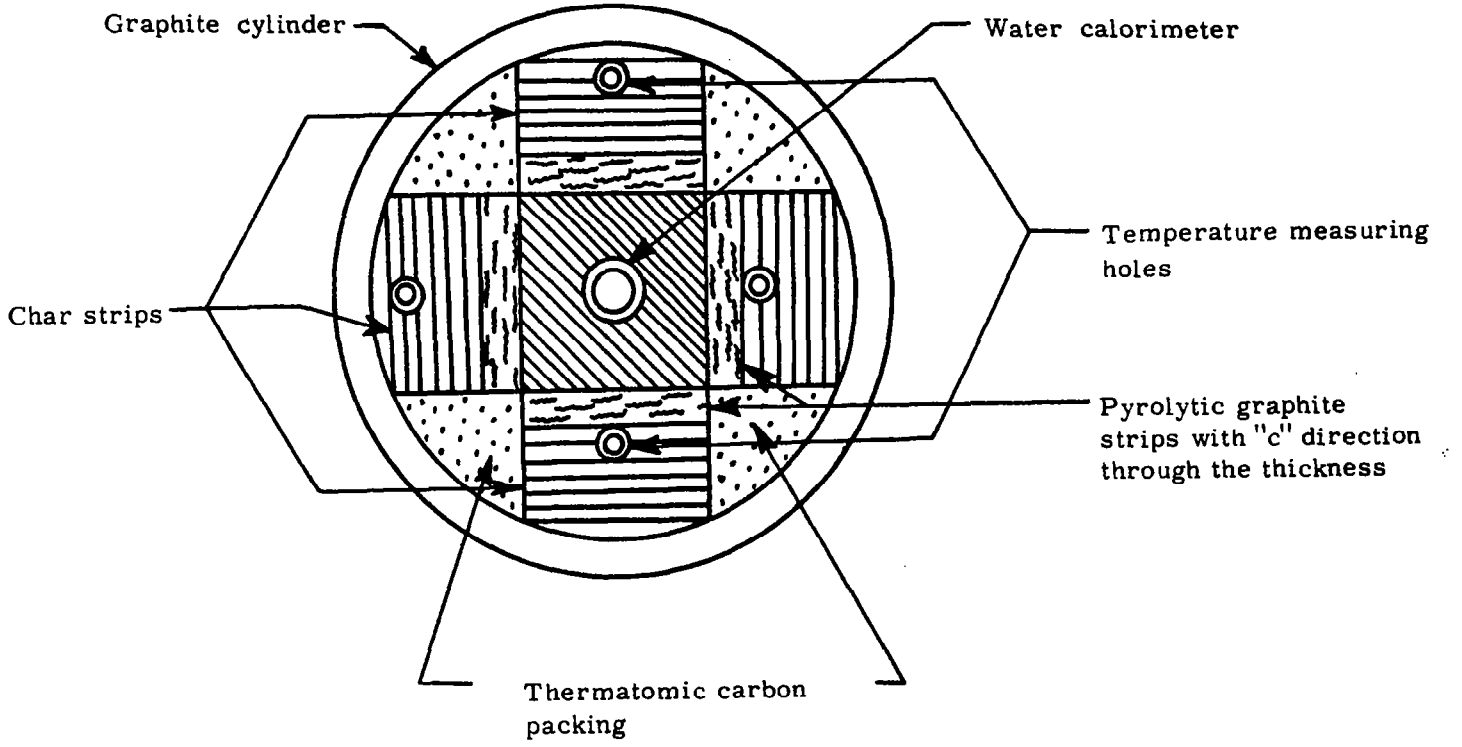


Figure 4. Strip specimen configuration used in radial inflow apparatus to determine the thermal conductivity of Narmco 4028 char in the across fiber direction

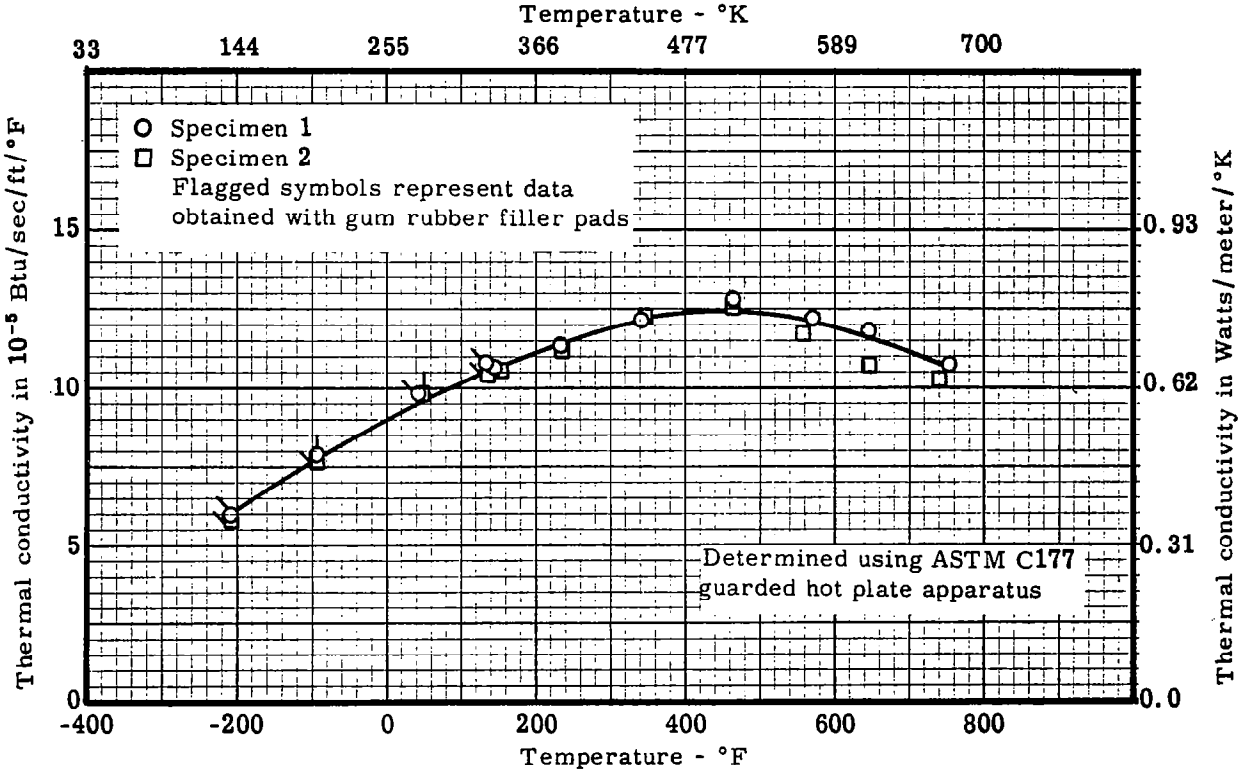


Figure 5. Thermal conductivity of virgin Narmco 4028 material in the across fiber direction

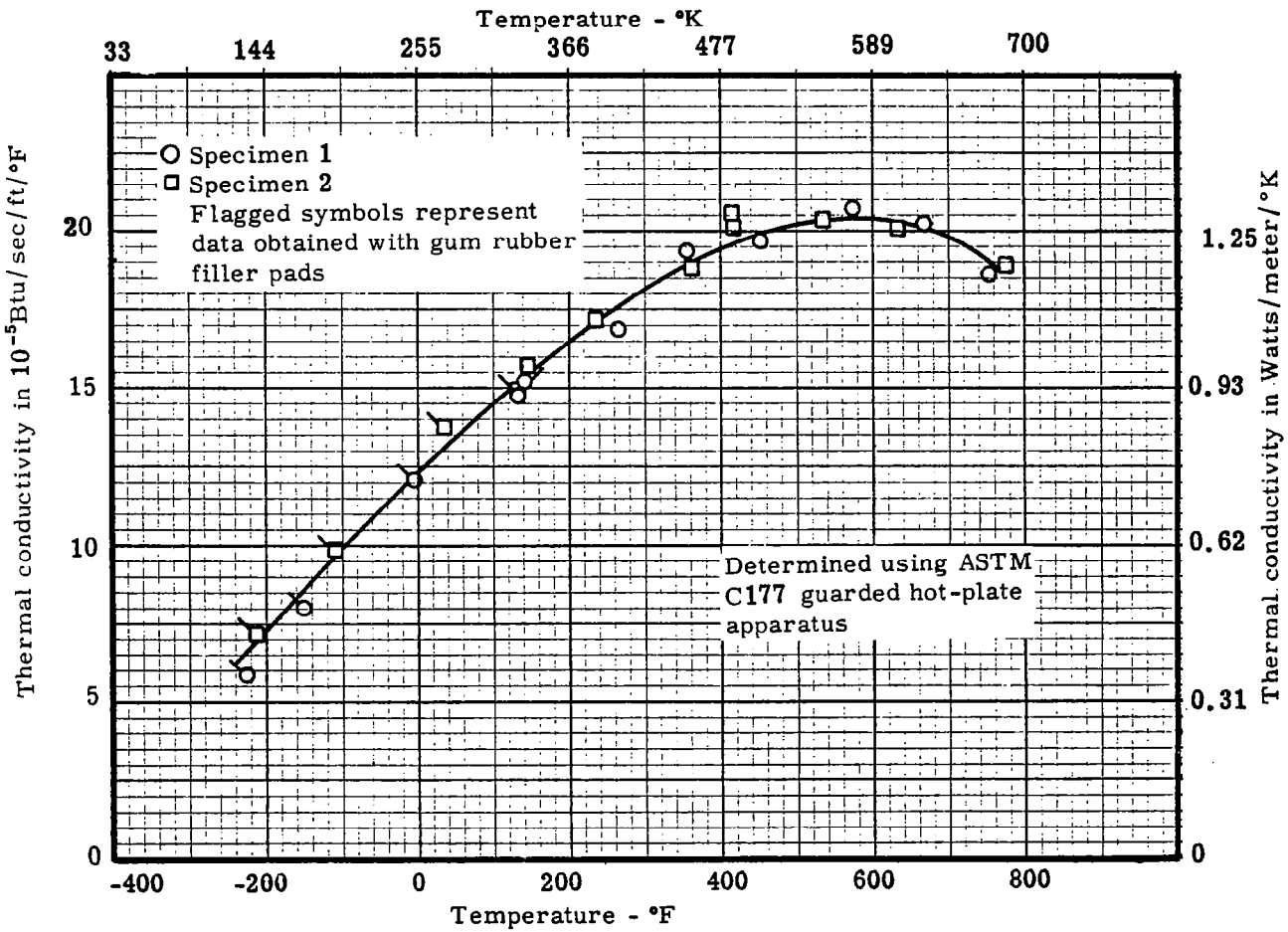


Figure 6. Thermal conductivity of virgin Narmco 4028 material in the with fiber direction

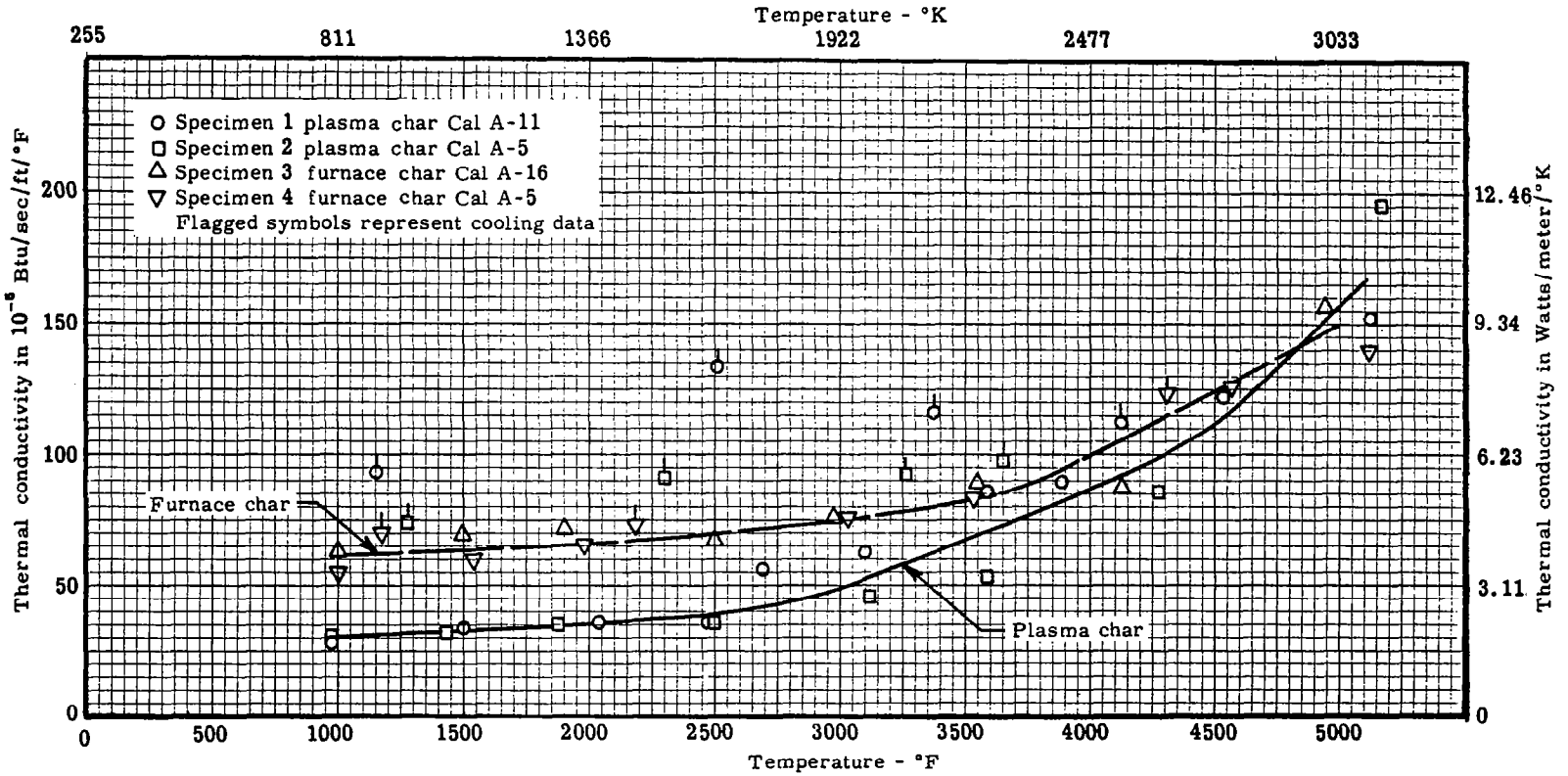
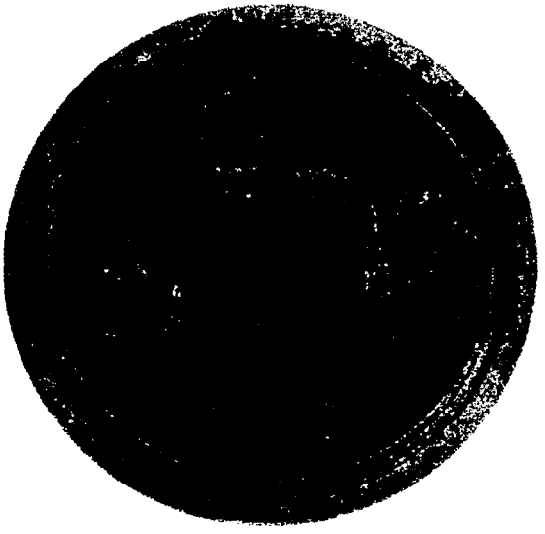


Figure 7. Thermal conductivity of Narmco 4028 char in the across fiber direction determined in radial inflow apparatus

Strip specimen assembly before exposure to thermal conductivity run. Plasma Char - Specimen 2

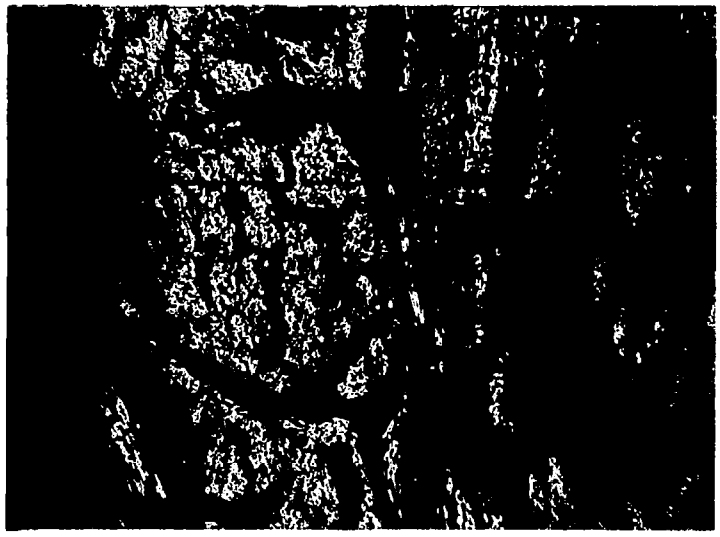
Strip specimen assembly after exposure to thermal conductivity run. Plasma Char - Specimen 2



Strip specimen assembly before exposure to thermal conductivity run. Furnace Char - Specimen 3

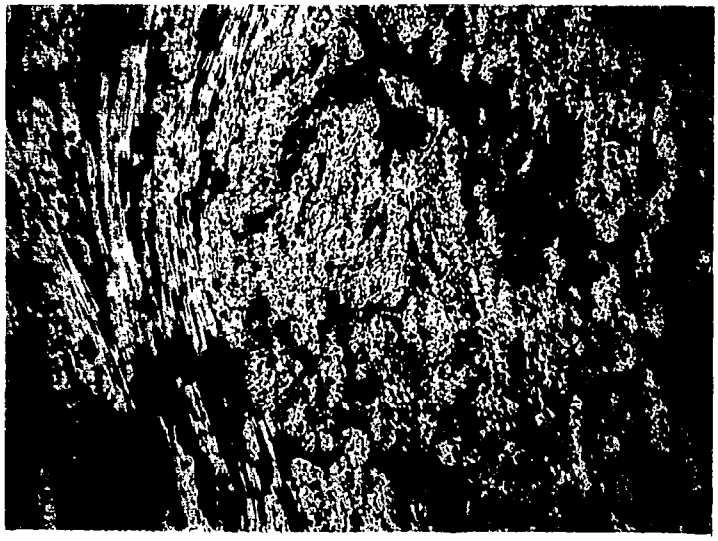
Strip specimen assembly after exposure to thermal conductivity run. Furnace Char - Specimen 3

Figure 8. Photographs of typical specimen assemblies of Narmco 4028 char before and after exposure to the thermal conductivity run



Thickness

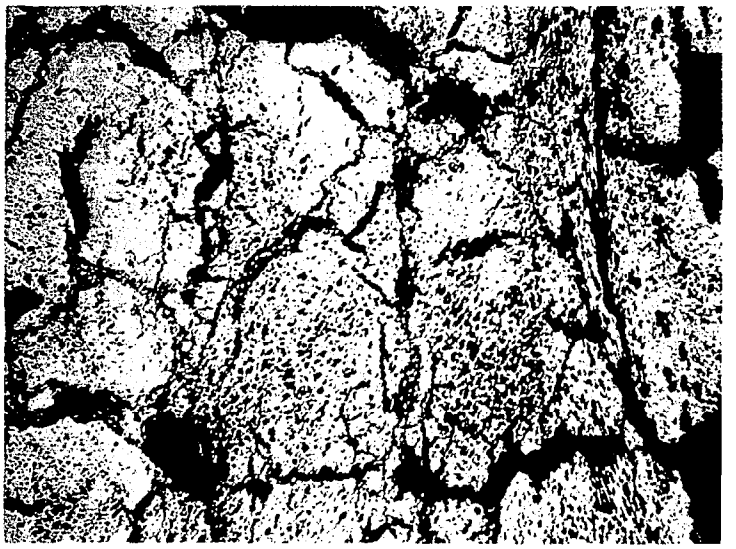
Before exposure (50X)



Thickness

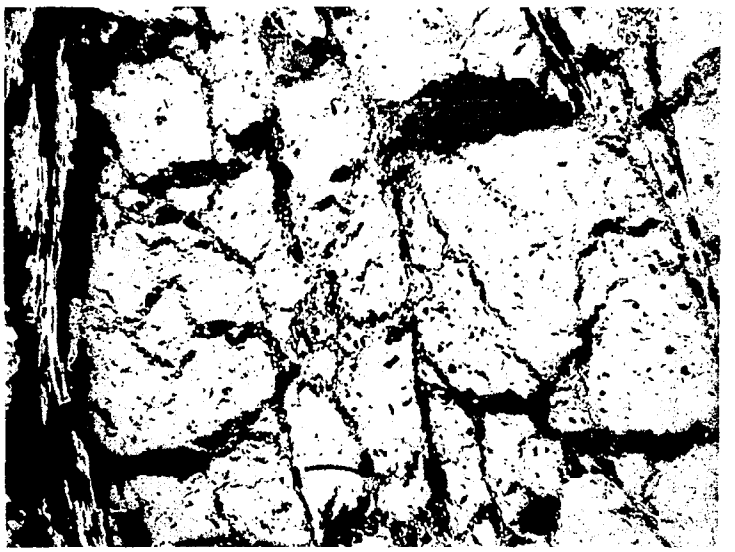
After exposure to thermal conductivity run (50X)

Figure 9. Photomicrographs of Narmco 4028 char (prepared with plasma) before and after exposure to the thermal conductivity run



Thickness

Before exposure (50X)



Thickness

After exposure to thermal conductivity run (50X)

Figure 10. Photomicrographs of Narmco 4028 char (prepared with furnace) before and after exposure to the thermal conductivity run

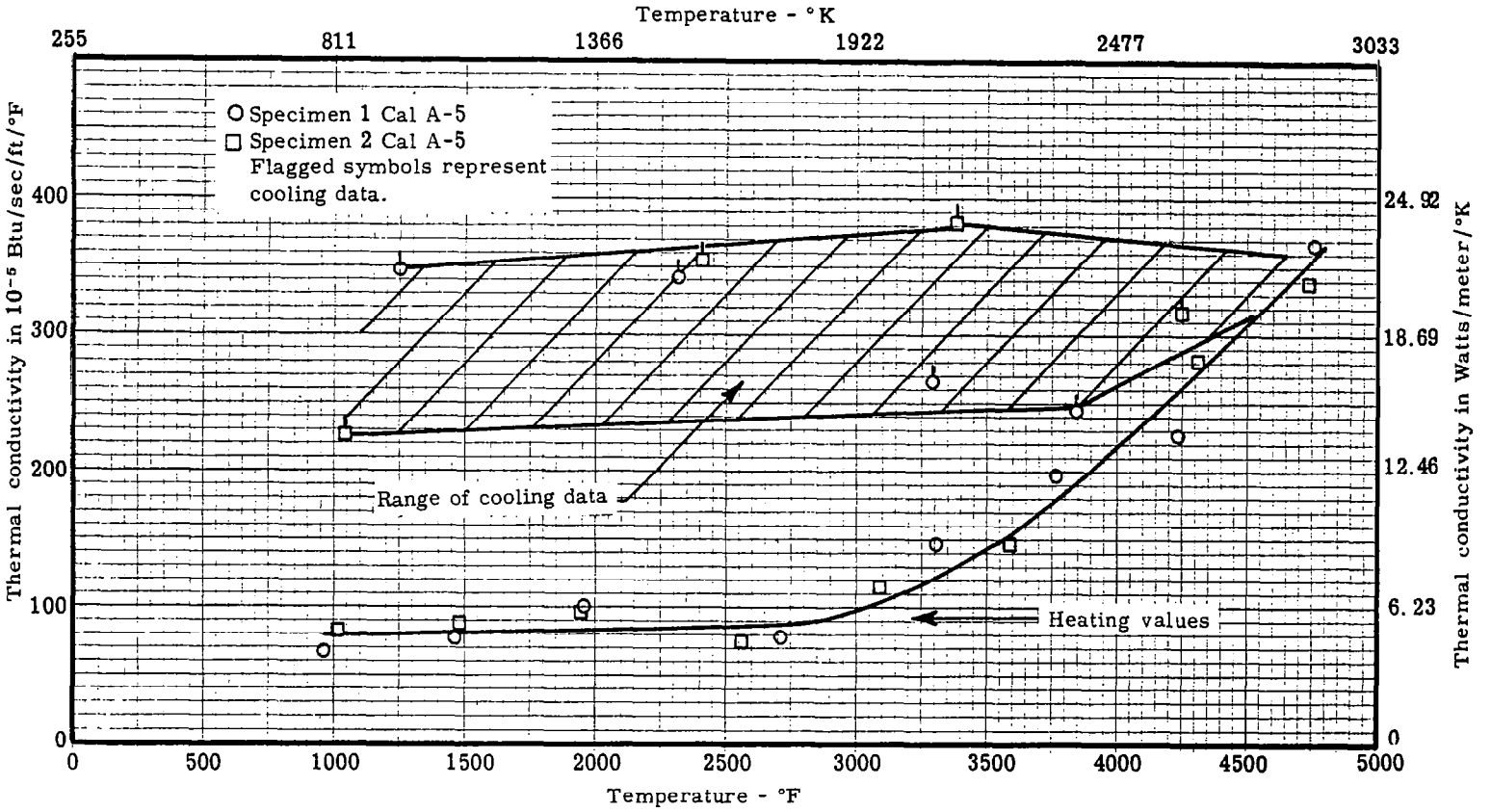


Figure 11. Thermal conductivity of Narmco 4028 char in the with fiber direction (Specimens precharred in plasma torch)

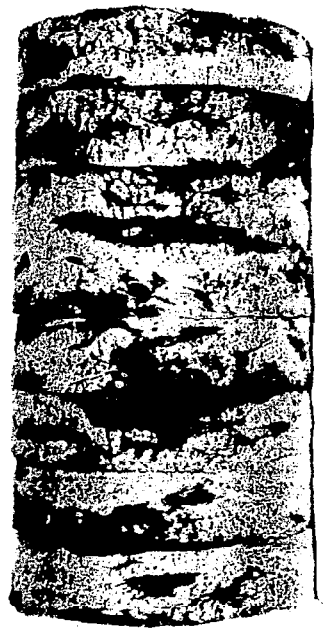
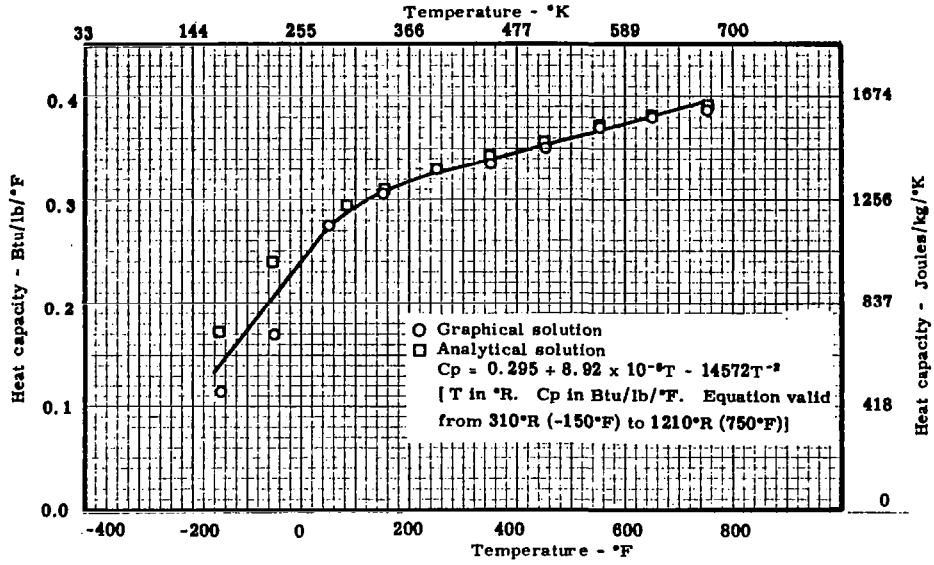


Figure 12. Photograph of with fiber thermal conductivity specimen showing condition after run to 5000°F (3033°K)(Specimen 1 - precharred in plasma torch)



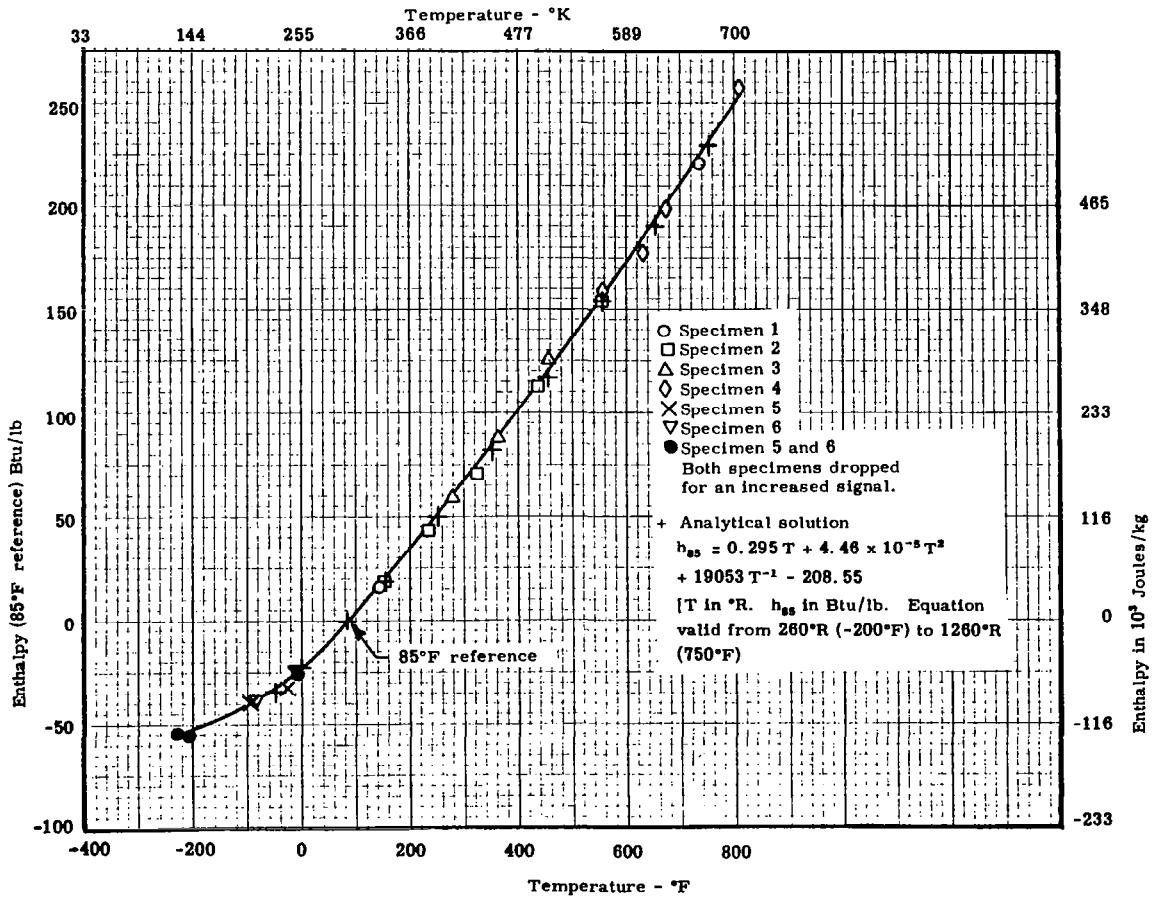


Figure 13. Enthalpy and heat capacity of virgin Narmco 4028 material

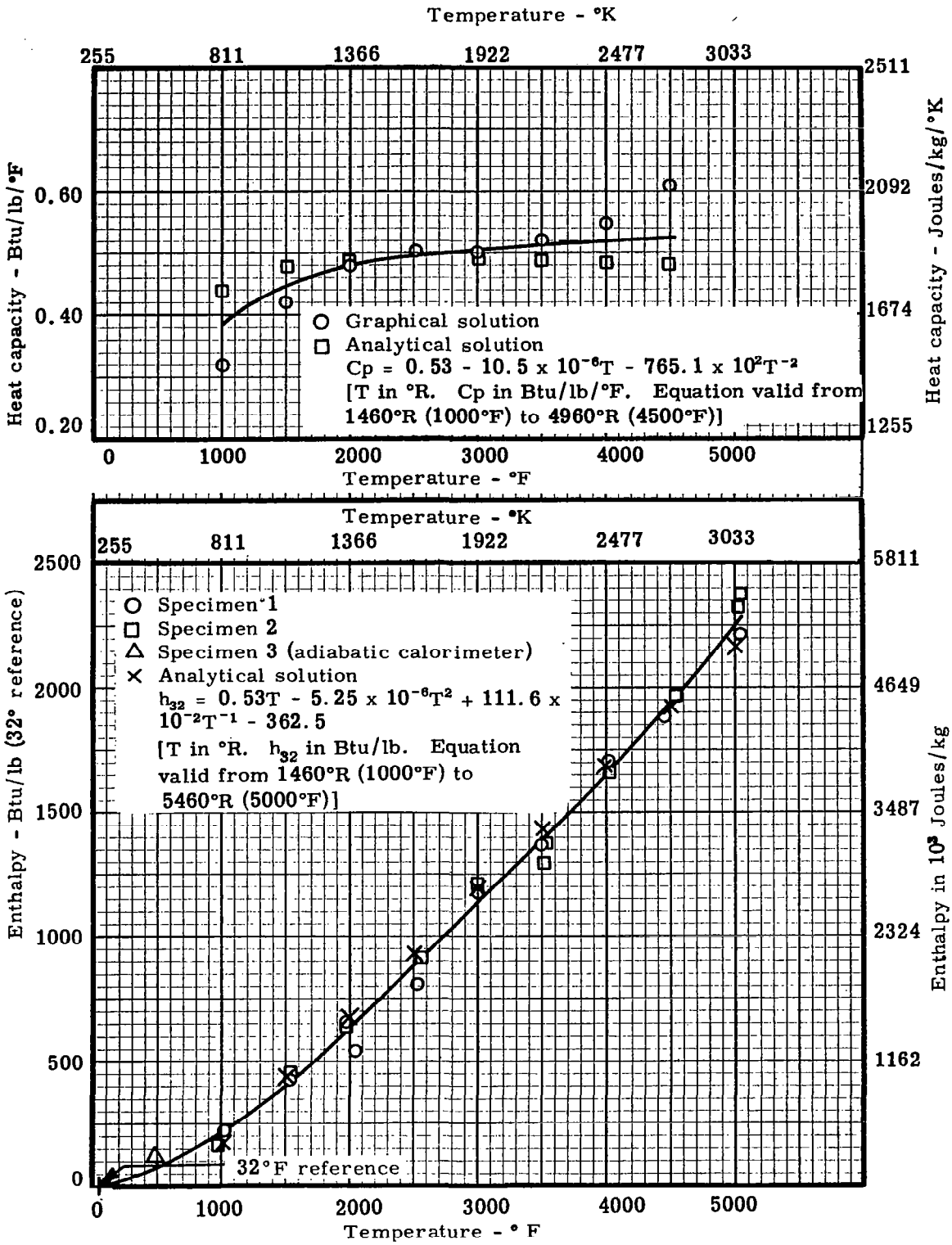


Figure 14. Enthalpy and heat capacity of Narmco 4028 char

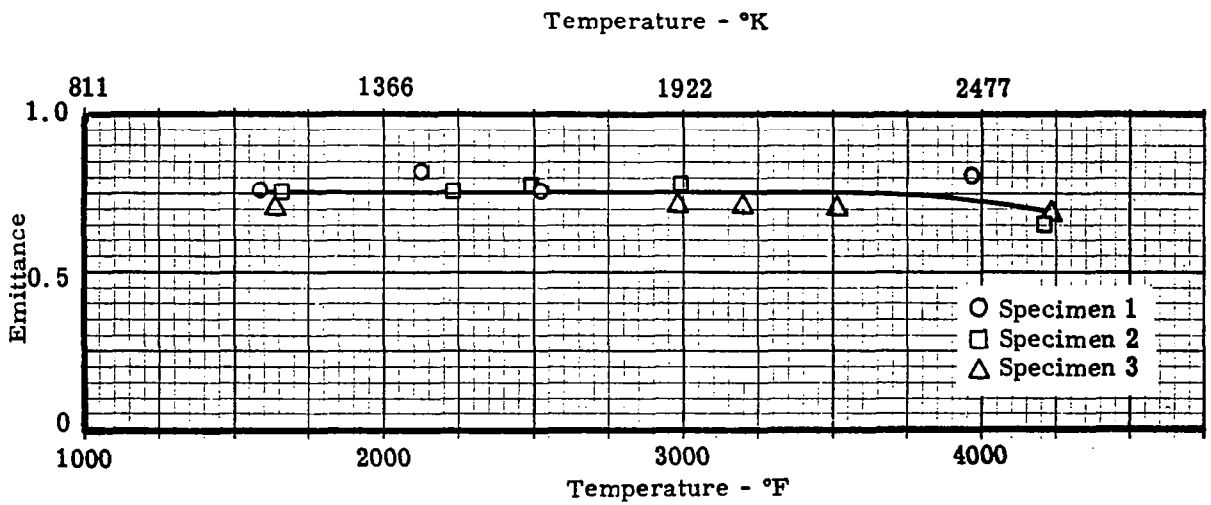


Figure 15. Total normal emittance of Narmco 4028 char

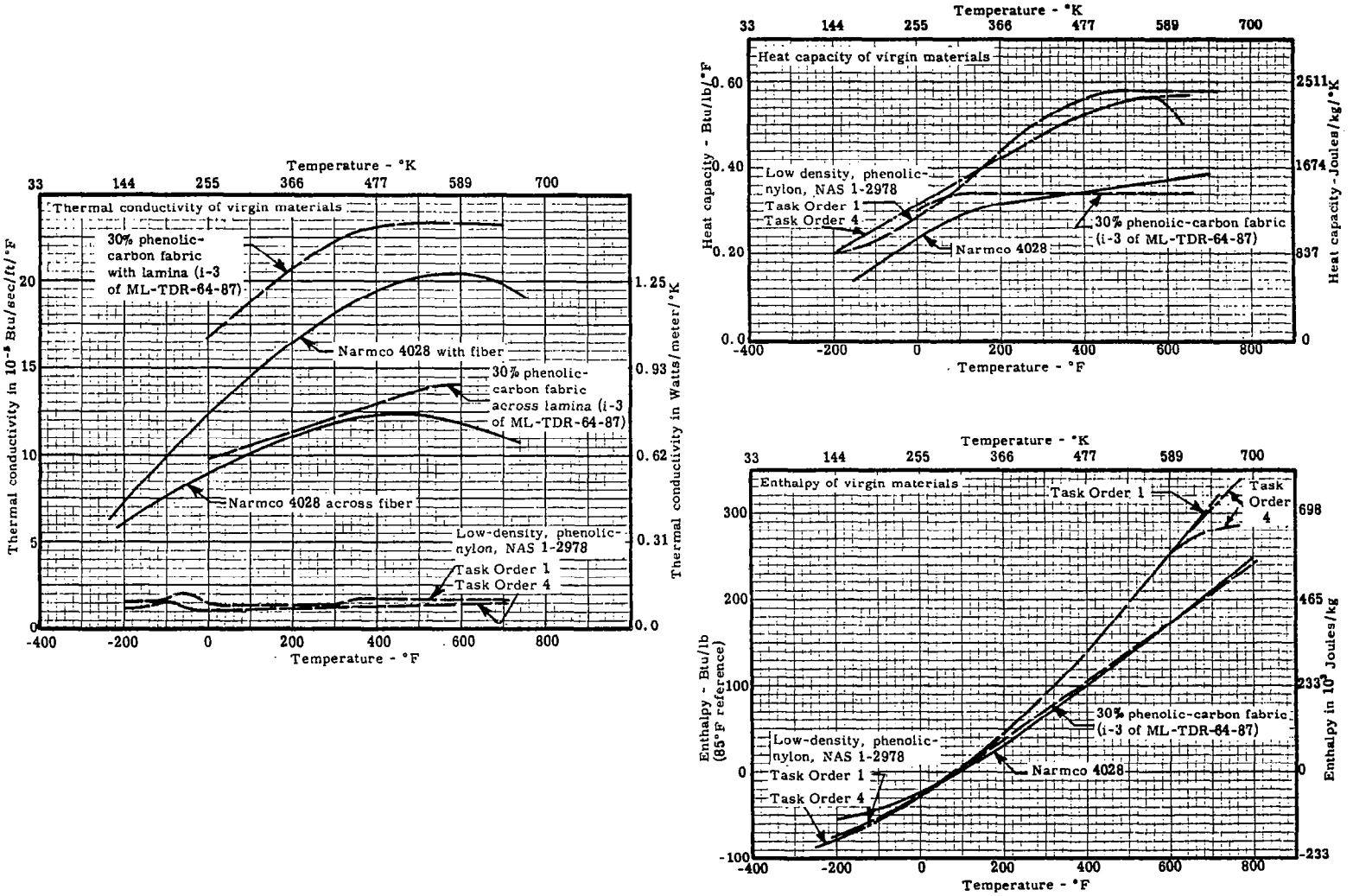


Figure 16. Thermal properties of virgin Narmco 4028 with comparative data on other virgin ablative materials

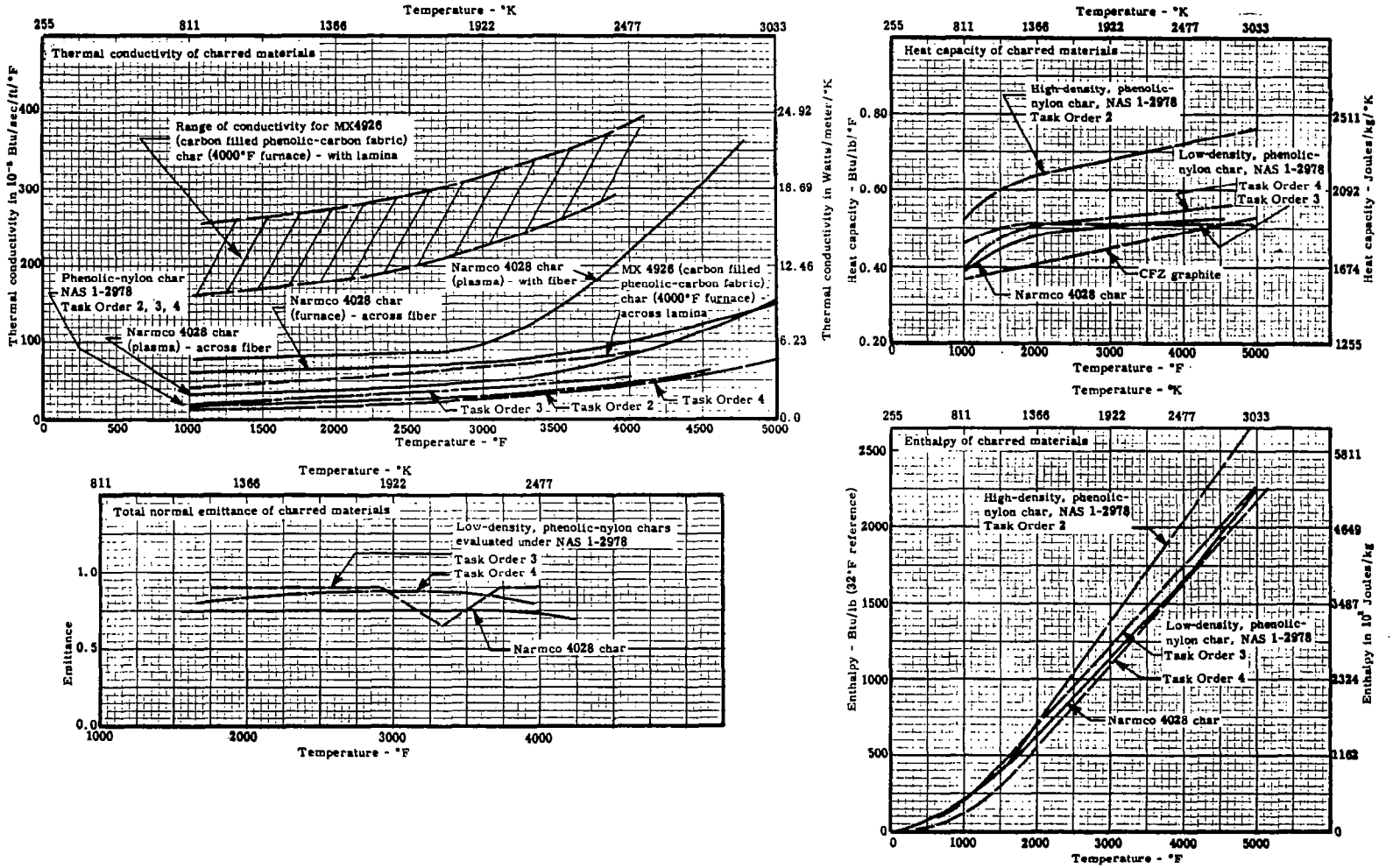


Figure 17. Thermal properties of Narmco 4028 char with comparative data on other charred ablative materials

TABLE 1

NARMCO 4028 SPECIFICATION SHEET
(The following was copied from the specification sheet on Narmco 4028 supplied by Narmco Materials Division)

Description

Narmco 4028 is a modified phenolic, carbon-fiber-reinforced, ablative and thermal insulating compound. It was developed primarily for use in rocket and missile parts which are subjected to high temperatures and to the impingement of high-velocity gases. Some of the more customary areas of application: Aft closures . . . Heat shields . . . Blast tubes.

Physical Properties

Reinforcement	-	Carbon fibers
Resin type	-	Phenolic
Standard form	-	$\frac{1}{4}$ inch fibers
Resin content	-	50% $\pm$ 3%
Specific gravity	-	1.4
Volatile content	-	4%
Bulk factor	-	4
Barcol hardness	-	65
Shrinkage	-	0.0005 to 0.001 inch per linear inch
Cured density	-	87 lb per cu ft
Storage	-	Up to 90 days, stored at 75°F or below. It is recommended that the material be refrigerated, and kept at 40°F.

Mechanical Properties

Ultimate compression	-	30,000 psi at room temp.
Ultimate flexural	-	10,000 psi at room temp.
Ultimate tensile	-	5,000 psi at room temp. (7,500 psi, using ASTM Dog Bone configuration)

TABLE 1 - Concluded

Thermal Properties

Thermal conductivity	-	3.8 $\frac{\text{Btu/in.}}{\text{hr/sq ft/°F}}$
Specific heat	-	0.25 Btu/lb/°F
Coefficient of thermal expansion	-	8×10^{-6} in. /in. /°F
Mold shrinkage	-	0.0005 inch per linear in.

Recommended Molding Procedure

Pre-heating. - Narmco 4028 can be pre-heated at 180°F in an air-circulating oven for thirty minutes. The configuration of the final part, and the type of molidng equipment to be used usually determine the requirement for pre-heating.

Curing. - Warm the mold to 300°F. Place the pre-heated Narmco 4028 in the mold, and apply 2,000 to 6,000 psi for one hour. (For large parts, it is recommended that the mold be loaded at a temperature of 200°F, and that the material be stage-cured by bringing the mold temperature up to 300°F as quickly as possible.)

NOTICE: Product data and parameters cited in this publication have been obtained in Narmco laboratories, using the materials under carefully-controlled conditions. The information, therefore, is believed to be accurate, and correctly stated. Data of this type may be considered to be indicative of representative properties obtainable. Narmco cannot accept responsibility for the mis-application of these products, or for their use under uncontrolled conditions.

TABLE 2

THERMAL CONDUCTIVITY OF VIRGIN NARMCO 4028 MATERIAL
(PHENOLIC-CARBON FIBER) IN THE ACROSS FIBER DIRECTION

Average specimen mean temperature - °F	Total heat input watts	Average specimen Δ T °F	Specimen thermal conductivity			Time to temp. hr[1]
			$\frac{\text{Btu in.}}{\text{hr ft}^2\ °\text{F}}$	$\frac{\text{in } 10^{-5}\ \text{Btu}}{\text{sec ft } °\text{F}}$	$\frac{\text{Watts}}{\text{meter } °\text{K}}$	
Specimen 1						
Gum rubber filler						
-209.75	6.85	85.20	2.62	6.06	0.38	3.5
- 98.95	14.53	138.15	3.42	7.92	0.49	3.0
40.56	9.20	69.76	4.29	9.93	0.62	2.8
134.32	4.56	31.78	4.67	10.81	0.67	3.5
Fiberfrax and gum rubber filler						
147.68	3.83	27.35	4.56	10.56	0.66	3.0
231.05	8.64	57.17	4.92	11.39	0.71	12.5
340.84	7.13	44.12	5.26	12.18	0.76	5.3
464.63	10.50	62.00	5.52	12.78	0.80	15.8
569.99	13.37	83.06	5.24	12.13	0.76	5.0
646.59	15.26	97.18	5.11	11.83	0.74	4.5
751.84	16.47	112.89	4.64	10.74	0.67	4.0
Specimen 2						
Gum rubber filler						
-208.49	7.02	85.28	2.52	5.83	0.36	3.8
- 97.39	14.97	138.78	3.31	7.66	0.48	2.8
45.14	9.60	69.38	4.24	9.81	0.61	3.5
137.45	4.70	32.06	4.50	10.42	0.65	13.0
Fiberfrax and gum rubber filler						
156.50	4.71	31.20	4.63	10.72	0.67	4.0
236.03	9.31	58.72	4.86	11.25	0.70	3.0
343.48	7.37	42.65	5.31	12.29	0.77	4.0
461.26	10.52	59.62	5.41	12.52	0.78	4.0
558.42	13.36	79.89	5.13	11.87	0.74	13.5
648.41	15.23	100.28	4.66	10.79	0.67	5.0
740.89	17.45	120.98	4.42	10.23	0.64	4.0

Notes:

Central diameter: 1.9 inches
Specimen thickness: Specimen 1 = 0.3756 inch (prior to the run)
0.3672 inch (after the run)
The change in thickness of Specimen 1 occurred at the 750°F point, therefore, the final thickness used to calculated this point.
Specimen 2 = 0.3540 inch (prior to the run)
0.3534 inch (after the run)
Since the change in thickness of Specimen 2 was less than 0.5%, the initial thickness (0.3540 inch) was used to calculate thermal conductivity.

[1]Time to temperature implies the time elapsed between adjustment of power and obtaining the data.

TABLE 3

THERMAL CONDUCTIVITY OF VIRGIN NARMCO 4028 MATERIAL
(PHENOLIC-CARBON FIBER) IN THE WITH FIBER DIRECTION

Average specimen mean temperature - °F	Total heat input watts	Average specimen ΔT °F	Specimen thermal conductivity			Time to Temp. hr[1]
			$\frac{\text{Btu in.}}{\text{hr ft}^2\ °\text{F}}$	$\frac{\text{in } 10^{-5}\ \text{Btu}}{\text{sec ft } °\text{F}}$	$\frac{\text{Watts}}{\text{meter } °\text{K}}$	
Specimen 1						
Gum rubber filler						
-227.32	5.42	68.25	2.58	5.97	0.37	3.0
-152.25	10.38	96.60	3.49	8.08	0.50	3.5
-2.03	6.63	41.28	5.21	12.06	0.75	2.4
140.52	5.34	26.55	6.53	15.11	0.94	4.0
Fiberfrax and gum rubber filler						
136.39	4.13	20.86	6.42	14.86	0.93	14.0
263.34	11.25	49.96	7.31	16.92	1.05	5.5
356.02	7.54	29.31	8.35	19.33	1.20	15.0
453.58	10.02	38.11	8.53	19.74	1.23	6.5
572.26	13.08	47.42	8.95	20.72	1.29	13.5
666.27	15.40	57.15	8.74	20.23	1.26	3.0
753.40	16.40	66.05	8.06	18.66	1.16	3.0
Specimen 2						
Gum rubber filler						
-217.06	6.99	73.98	3.08	7.13	0.44	3.0
-110.59	14.72	112.34	4.28	9.91	0.62	2.5
37.83	9.90	54.32	5.95	13.77	0.86	2.7
130.99	4.72	21.88	6.46	14.95	0.93	13.0
Fiberfrax and gum rubber filler						
154.10	4.94	23.75	6.80	15.74	0.98	6.0
238.44	10.31	45.32	7.43	17.20	1.07	13.0
359.86	8.01	32.12	8.14	18.84	1.17	4.7
New build up - resurfaced samples (new thickness)						
367.48	8.02	31.60	8.24	19.07	1.19	4.5
418.89	9.26	33.87	8.87	20.53	1.28	12.0
417.81	9.26	34.68	8.67	20.07	1.25	13.5
538.09	12.32	45.54	8.78	20.32	1.27	3.5
635.75	14.70	54.98	8.68	20.09	1.25	3.7
778.35	17.01	67.50	8.18	18.93	1.18	3.5

Notes:

Central diameter: 1.9 inches
Specimen thickness: Specimen 1 = 0.3744 inch (prior to the run)
0.3735 inch (after the run)
Specimen 2 = 0.3770 inch (prior to the run)
0.3747 inch (after resurface)
0.3744 inch (after the run)
Since the thickness change of both Specimens 1 and 2 was less than 0.5%, the initial thickness was used.

[1]Time to temperature implies the time elapsed between adjustment of power and obtaining the data.

TABLE 4

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR (PLASMA)
IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer readings) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity: Btu in. / hr ft² °F	Thermal conductivity: in 10⁻⁵ Btu / sec ft °F	Thermal conductivity: Watts / meter °K
Specimen 1 Run 4 Cal A-16	On 8:00 Read 9:05		Determined with thermocouples							
			1233	726	507	175				
			1238	730	508	185				
			1241	731	510	-				
			1241	731	510	173				
			1240	731	509	180				
			1241	731	510	-				
	Average		1239	730	509	178	984	12.6	29.2	1.82
	Read 9:45	2080	1814	1148	660	-				
		2090	1819	1153	666	279				
		2090	1822	1153	669	279				
		2095	1824	1154	670	-				
		2100	1829	1156	673	284				
		2100	1842	1157	685	295				
	Average	2092	1825	1153	671	284	1489	15.2	35.2	2.19
	Read 10:30	2590		1443	1147[1]	-				
		2600		1445	1155[1]	341				
		2610		1446	1164[1]	348				
		2605		1446	1159[1]	-				
		2600		1446	1154	357				
		2600		1445	1155[1]	-				
	Average	2601		1445	1156[1]	348	2023[3]	16.3[3]	37.7[3]	2.35[3]
	Read 11:05	3190		1785	1405[1]	396				
		3200		1790	1410[1]	397				
		3200		1793	1407[1]	404				
		3205		1795	1410[1]	409				
		3199		1791	1408[1]	403	2495[3]	15.5[3]	35.9[3]	2.24[3]
			Determined with optical pyrometer							
		3190	2355	1740	615	413				
		3200	2355	1780	605	413				
		3195			610	413	2683	24.3	56.2	3.50
	Read 12:30	3620	-	-	-	-				
		3620	2740	2160	580	454				
		3600	2710	2140	570	-				
		3610	-	-	-	459				
		3600	2790	2190	600	444				
		3600	2770	2160	610	448				
	Average	3608			590	451	3112	27.4	63.4	3.95

TABLE 4 - Continued

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR (PLASMA)
IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer readings) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity: Btu in. / hr ft² °F	Thermal conductivity: in 10⁻⁵ Btu / sec ft °F	Thermal conductivity: Watts / meter °K
Specimen 1 Run 1 (continued)	Read 1:30	4030	3060	2510	550	-				
		4050	2975	2440	535	544				
		4050	3010	2500	510	-				
		-	3080	2510	570	544				
		4030	-	-	-	-				
		4035	3140	2495	545	585				
		4030	-	-	-	-				
	Average	4038			542	558	3583	37.0	85.6	5.34
	Read 2:35	4370	3260	2730	530	-				
		4370	3310	2780	530	-				
		4370	3360	2770	590	617				
		4400	3380	2780	600	627				
		4390	3430	2860	570	625				
		-	3440	2840	600	619				
	Average	4376			570	622	3897	39.2	90.7	5.65
	Read 3:50	4960	-	-	-	727				
		4950	-	-	-	713				
		4940	-	-	-	-				
		4940	3810	3310	500	716				
		4940	3880	3360	520	-				
	Up 4:10	4940	3800	3360	440	-				
	Average	4945			487	719	4536	53.0	122.7	7.64
		5480	-	-	-	798				
	Read	-	4060	3620	440	786				
	4:25	-	4000	3580	420	801				
	Down	5480	4040	3590	450	790				
	4:35	-	4000	3580	420	800				
	Average	5480			433	795	5116	65.9	152.5	9.50
	Read 5:20	4550	-	-	-	-				
		-	-	-	-	697				
		-	3530	3080	530	-				
		-	3620	3100	520	694				
		4520	3600	3160	440	669				
		4550	-	-	-	-				
	Down 6:00	4550	-	-	-	661				
	Average	4542			497	680	4125	49.1	113.7	7.08

TABLE 4 - Continued

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR (PLASMA)
IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer readings) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen Δ T °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity: Btu in. / hr ft² °F	Thermal conductivity: in 10⁻⁵ Btu / sec ft °F	Thermal conductivity: Watts / meter °K
Specimen 1 Run 1 (continued)	Read									
	6:42	3700	2815	2450	365	538				
		3680	2888	2480	400	527				
		3680	2870	2500	370	525				
		-	2800	2540	-	-				
		-	2860	2470	390	556				
	Down	-	2980	2500	390	-				
	7:03									
	Average	3687			383	536	3365	50.2	116.2	7.24
	Read									
	7:42	2720	-	-	-	438				
		2690	2280	1920	340	428				
		-	2200	1950	250	448				
	Down	-	2220	1990	230	452				
	8:06	-	2150	1920	290	463				
	Average	2750			278	446	2516	57.6	133.3	8.31
			Determined with thermocouples							
	Read									
	9:10		1276	1035	241	227				
			1276	1036	241	227				
			1263	1046	212	242				
			1262	1044	218	242				
			1257	1042	215	242				
	Average		1267	1041	225	236	1154	37.7	87.3	5.44
Specimen 2 Run 1 Cal A-5	On 8:00 Read		Determined with thermocouples							
	9:00		1236	720	516	191				
			1245	727	518	199				
			1250	729	521	198				
			1253	731	522	191				
	Up 9:10		1257	733	524	196				
			1260	735	525	194				
	Average		1250	729	521	195	990	13.4	31.0	1.93
	Read									
	9:45	-	1770	1076	694	-				
		2030	1778	1082	696	284				
		-	1782	1084	698	282				
		2040	1784	1083	701	281				
		-	1786	1084	702	289				
	Up 9:55	2050	1789	1085	704	282				
	Average	2050	1782	1082	699	284	1432	14.6	33.8	2.11

TABLE 4 - Continued

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR (PLASMA)
IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer readings) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity: Btu in./hr ft² °F	Thermal conductivity: in 10⁻⁶ Btu/sec ft °F	Thermal conductivity: Watts/meter °K
Specimen 2, Run 1 (continued)	Read									
	10:20	-	2286	1448	838	-				
		2625	2290	1452	838	360				
		2630	2293	1451	842	-				
		-	2295	1452	843	366				
		2630	2299	1452	847	362				
		2635	2302	1453	849	361				
	Average	2660	2294	1451	843	362	1872	15.4	35.6	2.22
	Read									
	11:05	3220		1776	1444[1]	422				
		3220		1776	1444[1]	423				
		3230		1776	1454	420				
		3230		1777	1453[1]	404				
		3240		1778	1462[1]	-				
		3230		1778	1452[1]	-				
	Average	3227	–	1777	1452[1]	417	2502 [3]	15.5 [2]	35.9 [3]	2.24 [3]
			Determined with optical pyrometer							
	Read									
	12:15	3810	2860	1900	800	-				
		3800	2855	1975	855	459				
		3820	2890	1900	840	458				
		3810	2850	2070	870	451				
	Up	-	-	-	-	-				
	12:40	3820	-	-	-	465				
	Average	2812			841	458	3106	19.6	45.4	2.83
	Read									
	1:05	4230	3260	2450	810	486				
		4220	-	-	-	491				
		4230	3270	2460	810	478				
		4230	-	-	-	495				
		4230	3290	2560	730	492				
		4230	3300	2560	740	492				
	Up 2:06	4230	3300	2570	730	-				
	Average	4229			764	489	3587	23.0	53.2	3.32
	Read									
	1:50	4730	3540	2950	590	-				
	Up 2:06	4730	3520	2950	570	-				
		4740	3530	2980	550	591				
		4730	3480	2910	570	596				
		4740	3500	2930	570	613				
	Average	4734			570	600	4255	37.8	87.4	5.45

TABLE 4 - Concluded

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR (PLASMA)
IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer readings) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity: Btu in. / hr ft² °F	Thermal conductivity: in 10^{-5} Btu / sec ft °F	Thermal conductivity: Watts / meter °K
Specimen 2 Run 1 (continued)	Read									
	2:57	5420	-	-	-	728				
		-	3450	3170	280	715				
		-	3450	3130	320	-				
	Down									
	3:03	5420	3470	3160	310	711				
	Average	5420			303	718	5165	85.1	197.0	12.27
	Read									
	3:45	4070	3050	2600	450	583				
		4040	3090	2590	500	-				
		4030	-	-	-	-				
		4050	-	-	-	593				
	Down	4050	3060	2570	490	562				
	4:02	-	-	-	-	567				
	Average	4048			483	576	3642	42.8	99.1	6.17
	Read									
	4:35	3610	-	-	-	-				
		-	-	-	-	485				
		3630	2770	2290	480	-				
		-	2800	2340	460	508				
	Down	-	2850	2440	410	512				
	5:15	3580	2850	2430	420	-				
	Average	3640			442	502	3269	40.8	94.4	5.88
	Read									
	5:53	2650	2175	1800	375	-				
		-	2180	1855	325	385				
	6:02	2590	2140	1800	340	-				
		-	-	-	-	378				
	Down	-	-	-	-	417				
	6:25	2580	2140	1750	390	409				
	Average	2607			358	397	2306	39.8	92.1	5.74
			Determined with thermocouples							
	Read									
	7:10	-	1396	1164	232	219				
		-	1375	1161	214	205				
	Off	-	1361	1131	230	188				
	7:40	1500	1361	1133	228	194				
	Average	1500	1373	1147	226	202	1260	32.1	74.3	4.63

Notes:

1. ΔT obtained between outer face and inside hole temperature.
2. Thermal conductivity calculated with a factor (t/a) of 54.14 to accommodate the ΔT obtained between outer face and inside hole temperature.
3. Mean temperature calculated as average between outer face and inside hole temperature.
4. Mean temperature below 2000°F calculated as the average of thermocouple readings.
5. Mean temperature above 2000°F = T_{OF} - 0.84 ΔT; T_{OF} - outer face temperature
6. $K = \frac{t\,Q}{A\Delta T}$

where

K = thermal conductivity
t = distance between outside and inside hole = 0.186 in.
Q = heat to calorimeter gage
A = area of specimen = 0.187 in.²
ΔT = temperature drop from outside to inside hole

TABLE 5

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR
(FURNACE) IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Optical face temp. (corrected optical pyrometer reading) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity		
								Btu in. / hr ft² °F	in 10^{-5} Btu / sec ft °F	Watts / meter °K
			Determined with thermocouples							
Specimen 1 Run 1 (Calorimeter A-16)	On 8:00		1182	809	373	274				
	Read 8:45		1187	811	372	290				
			1186	813	373	287				
			1190	813	377	295				
			1192	812	378	288				
	Up 8:55		1194	815	379	285				
	Average		1188	813	375	286	1000	27.4	63.4	3.95
	Read 9:45	-	1755	1238	517	422				
		1980	1760	1245	515	437				
		-	1762	1246	516	438				
		1985	1762	1244	518	424				
		-	1761	1244	517	440				
	Up 9:54	1990	1767	1245	522	434				
	Average	1985	1761	1244	518	433	1502	30.0	69.4	4.33
	Read 10:30	2465	2210	1590	620	531				
		2465	2211	1591	620	547				
		-	2211	1589	622	541				
		2460	2215	1588	627	541				
		-	2220	1591	629	547				
	Up 10:42	2465	2225	1593	632	530				
	Average	2464	2215	1590	625	540	1902	31.0	71.8	4.47
			Determined with optical pyrometer							
	Read 11:15	3150	2425	1615	810	642				
		3160	2420	1640	780	630				
		3150	2410	1630	780	665				
		3170	2430	1620	810	664				
	Up 11:30	3160	2430	1610	820	622				
	Average	3155			800	645	2486	28.9	66.9	4.17
	Read 12:00	-	2830	2120	710	667				
		-	2865	2115	750	689				
		3600	2930	2153	777	686				
	Up 12:45	3600	2870	2130	740	700				
	Average	3600			744	686	2975	33.1	76.6	4.77

TABLE 5 - Continued

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR
(FURNACE) IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Optical face temp. (corrected optical pyrometer reading) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity		
								Btu in. / hr ft² °F	in 10^{-5} Btu / sec ft °F	Watts / meter °K
Specimen 1 Run 1 (continued)	Read 1:25	4110	3210	2530	680	-				
		4120	3220	2490	730	762				
		4135	3180	2500	680	745				
		4140	3205	2520	685	735				
	Up 1:40	4145	3230	2515	715	-				
	Average	4130			698	747	3544	38.4	88.9	5.54
	Read 2:15	4670	3560	2880	680	740				
		4690	3560	2910	650	-				
		4680	3560	2880	680	706				
		4690	3570	2930	640	692				
	Up 2:37	4690	3570	2910	660	694				
	Average	4684			662	708	4128	38.4	88.9	5.54
	Read 3:05	5240	3740	3350	390	652				
		5240	3680	3360	320	651				
		5240	3680	3350	330	647				
		5240	3670	3320	350	631				
		5250	3580	3280	300	640				
	Average	5242			338	644	4958	68.4	158.3	9.86
			Determined with thermocouples							
Specimen 2 Run 1 (Calorimeter A-5)	On 7:55 Read 8:35		1197	808	389	267				
			1203	811	392	261				
			1204	810	394	264				
			1205	810	395	258				
			1206	810	396	263				
	Up 8:45		1207	810	397	263				
	Average		1204	810	394	263	1007	24.0	55.6	3.46
	Read 9:10		1778	1249	529	387				
			1784	1255	529	386				
			1784	1254	530	382				
			1785	1254	531	376				
			1787	1254	533	381				
	Up 9:22		1787	1254	533	383				
	Average		1784	1253	531	383	1518	25.9	60.0	3.73
	Read 9:50	-	2264	1627	637	473				
		-	2266	1629	637	464				
		2640	2268	1628	640	478				
		-	2269	1628	641	492				
		2645	2271	1628	646	478				
	Up 10:02	-	2271	1628	643	474				
	Average	2642	2268	1628	640	476	1948	27.7	64.1	3.99

TABLE 5 - Continued

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR
(FURNACE) IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Optical face temp. (corrected optical pyrometer reading) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity		
								Btu in. / hr ft² °F	in 10^{-3} Btu / sec ft °F	Watts / meter °K
Specimen 2 Run 1 (continued)	Read 11:45	-	2715	2085	630	594				
		-	2688	2100	585	625				
		3620	2715	2090	625	602				
		-	2830	2130	700	627				
	Up 12:10	3640	2870	2100	770	628	___	___	___	___
	Average	3630			662	615	3074	33.4	77.3	4.82
	Read 12:45	4100	-	-	-	659				
		-	3040	2440	600	654				
		4100	3020	2400	620	652				
		-	3040	2430	610	-				
		-	-	-	-	658				
	Up 1:25	4110	3200	2440	800	-	___	___	___	___
	Average	4103			658	656	3550	35.8	82.9	5.16
	Read 1:55	4580	3570	2820	750	717				
		-	3550	2840	710	709				
		4610	3590	2845	745	699				
		-	3670	2930	740	681				
	Up 2:15	-	3740	2965	775	664	___	___	___	___
	Average	4595			744	694	3970	33.5	77.5	4.83
	Read 3:00	4940	3840	3400	440	696				
		-	3840	3390	450	709				
		4960	-	-	-	704				
		4960	3860	3320	540	768	___	___	___	___
	Average	4953			472	727	4557	55.3	128.0	7.97
	Read 3:50	5500	4100	3740	360	778				
		-	4180	3620	560	766	___	___	___	___
	Average	5500			460	772	5114	60.2	139.3	8.68
	Read 5:00	4660	3590	3120	470	611				
		4650	3530	3190	340	621				
		-	3460	3110	350	602				
	Down 5:30	-	3430	3000	490	625				
		4660	-	-	-	612	___	___	___	___
	Average	4657			412	614	4311	53.5	123.8	7.71

TABLE 5 - Concluded

THERMAL CONDUCTIVITY OF NARMCO 4028 CHAR
(FURNACE) IN THE ACROSS FIBER DIRECTION

Specimen and run number	Time	Optical face temp. (corrected optical pyrometer reading)	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity: Btu in. / hr ft² °F	Thermal conductivity: in 10^{-6} Btu / sec ft °F	Thermal conductivity: Watts / meter °K
Specimen 2 Run 1 (continued)	Read									
	6:33	3820	3205	2645	560	505				
		-	3210	2650	560	493				
		-	2940	2350	590	496				
	Down	3830	2980	2340	640	483				
	6:56	3830	2950	2380	570	508				
	Average	3827			584	497	3336	30.6	70.8	4.41
	Read									
	7:35	2150	-	-	-	369				
		-	2350	1900	450	369				
		2720	2315	1950	365	377				
	Down	-	2230	1770	460	400				
	8:05	2720	-	-	-	354				
	Average	2730			425	374	2373	31.6	73.1	4.56
			Determined with thermocouples							
	Read									
	8:55	1620	1475	1235	240	204				
		-	1471	1232	239	208				
	Off	-	1462	1221	241	205				
	9:07	1610	1455	1221	234	200				
	Average	1615	1466	1227	238	204	1346	30.8	71.3	4.44

1. Mean temperature below 2000°F calculated as the average of thermocouple readings.

2. Mean temperature above 2000°F = T_{OF} - 0.84 ΔT; T_{OF} - outer face temperature

3. $K = \frac{t\ Q}{A \Delta T}$

where

K = thermal conductivity
t = distance between outside and inside hole = 0.186 in.
Q = heat to calorimeter gage
A = area of specimen = 0.187 in.²
ΔT = temperature drop from outside to inside hole

TABLE 6

THERMAL CONDUCTIVITY OF THE NARMCO 4028 CHAR
(PREPARED IN PLASMA) IN THE WITH FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer reading) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity		
								Btu in. / hr ft² °F	in 10^{-3} Btu / sec ft °F	Watts / meter °K
			Determined with thermocouples							
Specimen 1 Run 1	On 7:55		1146	829	317	-				
	Read		1152	833	319	325				
	8:30		1156	836	320	325				
	Up 8:43		1159	838	321	-				
			1162	840	322	330				
			1164	840	324	331				
	Average		1156	836	320	328	996	29.1	67.4	4.20
	Read	1940	1676	1239	437	-				
	9:15	-	1676	1240	436	519				
	Up 9:45	-	1680	1242	438	519				
		-	1683	1244	439	518				
		-	1684	1246	438	512				
		1940	1683	1245	438	-				
	Average	1940	1680	1243	437	517	1462	33.6	77.8	4.85
	Read	-	2211	1702	509	-				
	9:55	-	2214	1705	509	-				
	Up	-	2217	1708	509	761				
	10:08	2505	2217	1708	509	784				
		-	2218	1709	509	782				
		2510	2219	1710	509	789				
	Average	2508	2216	1707	509	780	1962	43.5	100.7	6.27
	Read	3250	-	2173	1077[1]	-				
	10:50	3250	-	2175	1075_1	969				
	Up	3235	-	2173	1062_1	975				
	11:10	3250	-	2177	1073_1	973				
		3250	-	2183	1067_1	-				
		3270	-	2187	1083_1	970				
	Average	3251		2178	1073[2]	972	2714[3]	34.3[3]	79.4	4.95
			Determined with optical pyrometer							
	Read	3765	3150	2520	630	1312				
	12:00	3765	2980	2400	580	1269				
	Up	3775	3050	2530	520	1205				
	12:25									
	Average	3768			577	1262	3301	62.1	143.7	8.95

TABLE 6 - Continued

THERMAL CONDUCTIVITY OF THE NARMCO 4028 CHAR
(PREPARED IN PLASMA) IN THE WITH FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer readings) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity		
								Btu in. / hr ft² °F	in 10^{-3} Btu / sec ft °F	Watts / meter °K
	Read	4180	3240	2780	460	1520				
	12:50	4190	3280	2780	500	1529				
	Up	4180	3250	2765	485	1450				
	1:05	4180	3360	2810	550	1468				
	Average	4182			498	1492	3778	85.1	197.0	12.30
		4625	-	-	-	-				
		4660	3690	3150	540	1771				
		4655	3790	3190	600	-				
		4655	-	-	-	1817				
		4655	3680	3200	480	1812				
		4655	3720	3260	460	1809				
	Average	4651			520	1802	4236	98.4	227.8	14.20
	Read	5100	3840	3470	370	2394				
	2:25	5100	3940	3440	500	2401				
	Down	5100	4050	3620	430	2391				
	2:35	5100	4080	3670	410	2359				
	Average	5100			428	2386	4753	158.3	366.4	22.83
	Read	4260	3340	2830	510	1896				
	3:15	4260	3320	2800	520	1903				
	Down	4240	3320	2780	540	1912				
	3:30	4240	3290	2800	490	1915				
	Average	4250			516	1907	3833	105.0	243.0	15.14
	Read	3605	-	-	-	1627				
	4:15	3615	2880	2430	450	1648				
	Down	3615	2880	2490	390	1607				
	4:35	3605	2900	2540	360	1602				
	Average	3610			400	1621	3286	115.1	266.4	16.60
	Read	2505	2020	1820	200	1169				
	5:05	2490	2025	1815	210	1132				
	Down	2495	2030	1790	240	1072				
	5:20	2480	2030	1820	210	1097				
	Average	2492			215	1117	2318	147.6	341.6	21.28
			Determined with thermocouples							
	Read									
	5:55		1204	1097	107	-				
			1201	1097	104	554				
			1195	1091	104	547				
			1190	1086	104	-				
			1186	1082	104	554				
			1174	1072	102	540				
	Average		1192	1088	104	549	1140	150.0	347.2	21.63

TABLE 6 - Continued

THERMAL CONDUCTIVITY OF THE NARMCO 4028 CHAR
(PREPARED IN PLASMA) IN THE WITH FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer readings) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity		
								Btu in. / hr ft² °F	in 10⁻⁴ Btu / sec ft °F	Watts / meter °K
			Determined with thermocouples							
Specimen 2 Run 1	On 7:20		1138	864	274	339				
	Read		1139	866	273	351				
	8:05		1139	865	274	341				
	Up 8:15		1146	868	278	341				
			1148	870	278	339				
			1149	871	278	351				
	Average		1143	867	276	344	1005	35.4	81.9	5.10
	Read	1960	1664	1285	379	-				
	8:50	-	1667	1287	380	562				
	Up 9:02	-	1669	1287	382	546				
		-	1667	1285	382	-				
		-	1667	1284	382	532				
		1960	1669	1285	383	544				
	Average	1960	1667	1286	381	546	1476	40.7	94.2	5.87
	Read		2183	1699	484	708				
	9:40	2515	2185	1699	486	720				
	Up 9:54		2186	1698	488	711				
		2510	2187	1698	489	698				
			2189	1697	492	705				
		2510	2191	1699	492	703				
	Average	2512	2187	1698	489	708	1942	41.1	95.1	5.93
	Read	3080	-	2055	1025	-				
	10:25	3105	-	2056	1049	852				
	Up	3050	-	2057	993	848				
	10:42	3050	-	2055	995	844				
		3050	-	2051	999	844				
		3050	-	2051	999	-				
	Average	3064		2054	1010[1]	846	2559[3]	31.8[2]	73.6	4.59
			Determined with optical pyrometer							
	Read									
	11:10	3570	2785	2150	635	-				
	Up	3595	2795	2185	610	1095				
	11:25	3600	-	-	-	1090				
		3605	-	-	-	1096				
		3595	2850	2230	620	-				
	Average	3593			622	1094	3089	50.0	115.7	7.21
	Read	4100	3340	2720	620	-				
	11:55	-	3330	2690	640	1421				
	Up	4110	-	-	-	1394				
	12:10	4120	3350	2720	630	1406				
		-	3360	2720	640	1406				
	Average	4110			632	1407	3598	63.2	146.3	9.11

TABLE 6 - Concluded

THERMAL CONDUCTIVITY OF THE NARMCO 4028 CHAR
(PREPARED IN PLASMA) IN THE WITH FIBER DIRECTION

Specimen and run number	Time	Outer face temp. (corrected optical pyrometer readings) °F	Outside hole temp. °F	Inside hole temp. °F	Specimen ΔT °F	Heat flow to calorimeter Btu/hr	Mean temperature °F	Thermal conductivity: Btu in. / hr ft² °F	Thermal conductivity: in 10⁻³ Btu / sec ft °F	Thermal conductivity: Watts / meter °K
	Read	4640	3700	3330	370	1731				
	12:35	4625	3690	3310	380	1751				
	Up	4625	3700	3280	420	1730				
	12:47	4625	3750	3300	450	1727				
	Average	4629			405	1735	4301	121.7	281.7	17.55
	Read	5055	4000	3640	360	2055				
	12:55	5055	4010	3600	410	2074				
	Down	5065	4030	3620	410	2053				
	1:10	5065	4030	3610	420	2077				
	Average	5060			400	2065	4736	146.6	339.3	21.14
	Read									
	1:40	4555	3670	3290	380	1855				
	Down	4560	3670	3280	390	1836				
	1:50	4570	3650	3260	390	1854				
		4555	3680	3300	380	1861				
	Average	4560			385	1852	4248	136.6	316.2	19.70
	Read	3570	2830	2610	220	1442				
	2:30	3585	2810	2560	250	1427				
	Down	3575	2850	2470	260	1362				
	2:45	3570	2830	2560	270	1419				
		3570	2820	2590	230	1466				
	Average	3574			246	1429	3375	165.0	381.9	23.79
	Read	2545	2050	1865	185	994				
	3:25	2565	2070	1860	210	960				
	Down	2560	2060	1880	180	1023				
	3:40	2580	2070	1880	190	1010				
		2540	2055	1880	175	1037				
	Average	2554			188	1009	2402	152.4	352.8	21.98
			Determined with thermocouples							
	Read		1110	982	128	-				
	4:35		1108	983	125	431				
	Off 4:45		1105	980	125	-				
			1103	978	125	432				
			1100	975	125	435				
			1097	972	125	431				
	Average		1104	978	126	433	1041	97.5	225.7	14.06

Notes:

[1] Δ T obtained between outer face and inside hole temperature.

[2] Thermal conductivity calculated with a factor $\left(\frac{\ln R_o/R_i}{2\pi L}\right)$ of 37.9 to accommodate the ΔT obtained between outer face and inside hole temperatures.

[3] Mean temperature calculated as average between outer face and inside hole temperature.

[4] Mean temperature below 2000 °F calculated as the average of thermocouple readings.
Mean temperature above 2000°F = T_{OF} - 0.81 ΔT; T_{OF} - outer face temperature.

[5] $K = \frac{\ln (R_o/R_i)}{2\pi L} \frac{Q}{\Delta T}$

where K = thermal conductivity
R_o = outside radius = 0.4062 inch
R_i = inside radius = 0.2187 inch
Q = heat to calorimeter
ΔT = temperature drop from hot to cold hole on the outside and inside radius respectively
L = gage length of calorimeter = $\frac{1}{8}$ inch

TABLE 7

ENTHALPY OF VIRGIN NARMCO 4028 MATERIAL (PHENOLIC-CARBON FIBER)

Spec. and run no.	Initial cup temp. °F	Final cup temp. °F	Change in cup temp. °F	Initial sample temp. °F	Time to temp. min [1]	Initial wt. of sample gm	Final wt. of sample gm	Enthalpy $h = \frac{K}{W_s}(t_2 - t_1)$ Btu/lb	Enthalpy above 85°F reference Btu/lb
Spec 1									
Run 1	77.86	78.70	0.84	143.0	32	5.7003	5.6960	17.58	15.86
2	80.74	90.35	9.61	735.3	50	5.6960	5.2683	219.57	221.39
Spec 2									
Run 1	78.83	80.83	2.00	151.0	35	12.3545	12.3513	19.49	18.33
2	78.17	82.74	4.57	236.3	49	12.3513	12.3450	44.52	43.86
3	77.23	84.61	7.38	321.3	32	12.3450	12.3348	72.04	71.92
4	84.48	95.70	11.22	433.7	33	12.3348	12.3083	109.72	113.19
5	79.91	95.09	15.18	556.7	35	12.3083	12.1050	150.95	154.24
Spec 3									
Run 1	82.57	85.96	3.39	277.0	29	6.8976	6.8941	59.22	59.52
2	79.77	84.83	5.06	361.7	34	6.8941	6.8791	88.43	88.38
Spec 4									
Run 1	81.09	86.96	5.87	457.3	29	5.7053	5.6582	124.88	125.54
2	77.95	85.35	7.40	555.0	37	5.6582	5.5796	159.52	159.64
3	81.74	89.83	8.09	630.0	32	5.5796	5.5039	176.88	178.46
4	84.43	93.17	8.74	673.3	35	5.5039	5.4113	194.42	197.16
5	74.41	85.39	10.98	811.7	28	5.4113	5.1633	256.07	256.21
Spec 5									
Run 1	76.17	74.50	- 1.67	- 93.0	56	5.4825	5.4944	- 36.68	- 38.98
2	84.61	83.14	- 1.47	- 28.3	23	5.4944	5.4929	- 32.26	- 32.80
Spec 6									
Run 1	75.04	73.39	- 1.65	- 86.7	28	5.7391	5.7540	- 34.57	- 37.07
2	82.91	81.78	- 1.13	- 12.3	31	5.7540	5.7526	- 23.66	- 24.47
Specs 5, 6									
Run 1	76.00	72.32	- 3.68	-230.0	41	8.2165	8.2052	- 54.02	- 56.29
2	72.36	68.73	- 3.63	-209.0	30	8.2052	8.2051	- 53.35	- 56.48
3	87.39	85.65	- 1.74	- 6.5	17	8.2051	8.2043	- 25.52	- 25.34

[1]Time to temperature implies the time elapsed between inserting specimen in the furnace and dropping specimen into the calorimeter cup

TABLE 8

ENTHALPY OF THE NARMCO 4028 CHAR

Specimen number	SRI run number	Drop temperature °F	Initial weight grams	Final weight grams	Enthalpy from drop temperature to 32°F Btu/lb	Mean temperature for heat capacity °F	Heat capacity by slope measurement Btu/lb/°F	Heat Capacity by least squares curve fit to $C_p = 0.53 - 10.5 \times 10^{-6} T - 765.1 \times 10^{2} T^{-2}$ [1] Btu/lb/°F
1	1	1024	3.415	3.370	212.0	1000	0.32	0.44
1	2	1524	3.370	3.350	412.3	1500	0.42	0.48
1	3	2040	3.350	3.335	547.4	2000	0.48	0.49
1	4	1990	3.335	3.310	652.3	2500	0.50	0.49
1	5	2520	3.310	3.290	810.7	3000	0.50	0.49
1	6	2520	3.290	3.280	919.6	3500	0.52	0.49
1	7	3005	3.280	3.270	1184.6	4000	0.55	0.49
1	8	3500	3.270	3.260	1363.6	4500	0.61	0.48
1	9	4015	3.260	3.255	1707.1			
1	10	4455	3.255	3.250	1885.6			
1	11	5030	3.250	3.235	2218.2			
2	1	972	3.005	2.975	160.1			
2	2	1560	2.975	2.965	455.1			
2	3	1985	2.965	2.945	641.5			
2	4	2540	2.945	2.935	908.7			
2	5	2995	2.935	2.920	1212.4			
2	6	3515	2.920	2.915	1296.2			
2	7	3530	2.915	2.910	1374.8			
2	8	4020	2.910	2.905	1655.9			
2	9	4540	2.905	2.900	1965.3			
2	10	5035	2.900	2.890	2389.6			
2	11	5045	2.890	2.835	2318.4			

[1] In equation T in °R. Equation valid from 1460°R (1000°F) to 4960°R (4500°F).

TABLE 9

TOTAL NORMAL EMITTANCE OF NARMCO 4028 CHAR

Time	Observed temperature °F	Radiometer output millivolts	True temperature °F	Emittance
Specimen 1				
On 10:55				
11:05	1503	0.214	1590	0.77
11:12	1980	0.575	2121	0.82
11:21	2325	1.011	2514	0.81
11:29	3300	3.553	3651	0.76
11:39	3600	5.441	3970	0.81
Specimen 2				
On 2:24				
2:31	1572	0.249	1667	0.78
2:39	2067	0.629	2232	0.76
2:46	2305	0.961	2496	0.79
2:53	2740	1.817	2993	0.79
3:00	3720	5.132	4216	0.65
Specimen 3				
On 10:55				
11:02	1549	0.219	1650	0.70
11:10	2720	1.653	2496	0.71
11:15	2880	2.035	3186	0.71
11:21	3160	2.876	3517	0.70
11:26	3765	5.554	4240	0.69

NASA-Langley, 1967 —— 17

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546